RF Front Ends for Mobile Devices 2019

Abstract:

This report tracks all of the RF components used in 2G/3G/LTE/5G terminals, including smartphones, feature phones, tablets, PCs, hotspots, and IoT devices. Components such as amplifiers, filters, switches, tuners, and LNAs are included. Front End Modules that combine PA/filter/switch/other functions are also included, as well as quadplexers, antenna-plexers, and other specialty RF components. This year's report also includes a forecast for mm-wave RF front ends.

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June 2019

MOBILE EXPERTS

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RF FRONT ENDS FOR MOBILE DEVICES 2019

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1 EXECUTIVE SUMMARY

This growth market has slowed down. After 25 years of continuous solid growth, we now have a situation where the unit growth of smartphones has completely stopped, and RF content growth is low enough that natural price erosion roughly offsets the new content.

Suppliers in this market need to adjust to the realities of a mature market, where dog-eat-dog competition will dominate decision-making at many levels. We expect the lower tiers of the market to slow down their product life cycles to spread R&D costs over a longer time and higher volume. The premium tier of the market will continue to iterate quickly, with 5G entering the fray.

A few factors are important to the

- 5G will drive renewed replacement of smartphones;
- 5G will add a few new bands and growth in complexity;
- 4x4 MIMO is driving additional RF content in handsets;
- Carrier Aggregation requires more complex RF filter assemblies;
- 5G mm-wave will become significant, if not in smartphones then in hotspots/tablets/CPEs;
- And IoT growth is starting which will become moderately significant over the longer term.

The net growth of the market was only about 2% in 2018, and will be only about 1% in 2019. Longer term growth will result in an RFFE CAGR of 4% through 2024. One reason for the low market growth rate is our expectation of strong price erosion in the RFFE market in the 2020-2023 timeframe, driven by the entry of Qualcomm into the market for FEMs. Millimeter wave growth drives one opportunity for upside, and technical features such as wideband filters will offer some differentiation. But overall, this market area is maturing and becoming less technically driven or growth driven.

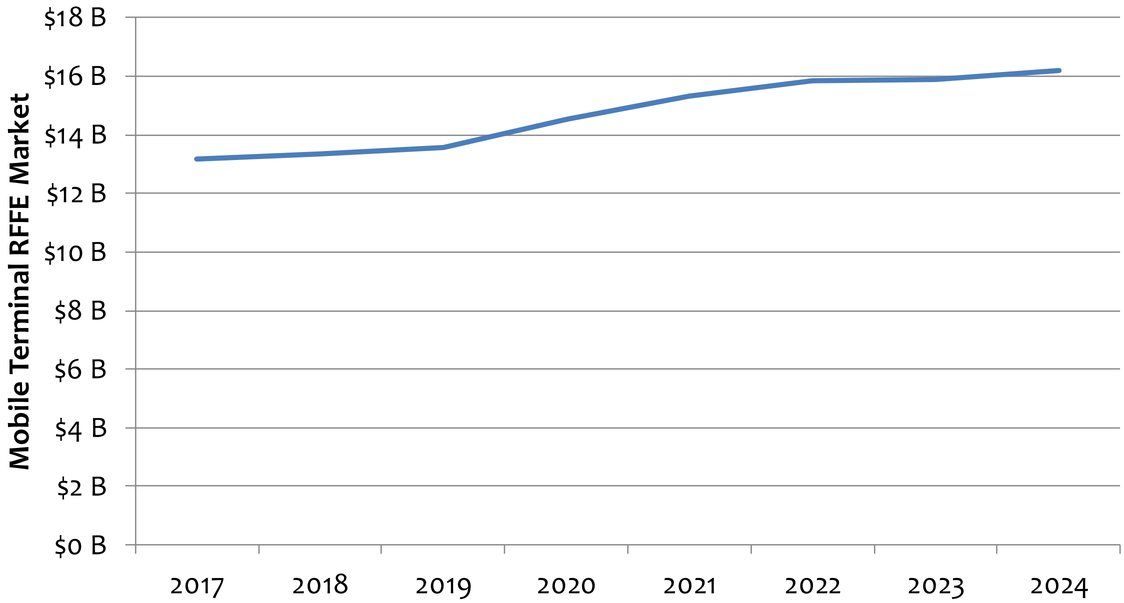


Chart 1: RFFE Market Forecast, 2017-2024

Source: Mobile Experts

New technologies such as Thin-Film SAW, along with "RF Artificial Intelligence", hold the promise of substantial change in the RFFE market in the future. Some new fundamental technologies have emerged which point the way toward possible integration of filter elements, PA elements, switch elements, and logic all on CMOS wafers. If on-chip integration of these wildly different functions can be achieved, then a completely new level of density and performance will be achieved.

One important strategic element is the need for communication and co-design between the modem and the RF section. Envelope tracking in a 5G world demands intimate design collaboration between these different functions. RF Artificial Intelligence (adapting the filtering and PA functions to suit the waveform, not the wider block of frequencies) will also demand very tight co-design between modem and RFFE. This means that independent RF companies should consider partnering with major modem suppliers.

In terms of market share, we now have a pretty evenly spread market between Broadcom, Skyworks, Qorvo, and Murata. Qualcomm is rising in market share currently, quickly approaching the top tier. Several other companies occupy niche positions.

2 MARKET OVERVIEW

Growth in the RF Front End market has been driven by multiple factors over the past 30 years, with unit growth compounding with growing RF content. It's been a rich growth environment for a long time.

Growth in the RF Front End (RFFE) market is driven by a few key factors:

- Smartphone growth;
- IoT growth;
- Increasing numbers of bands per terminal;
- Increasing MIMO order;
- Uplink MIMO and Uplink CA; and
- Increasing complexity or difficulty in RF requirements.

The first bullet point is running out of gas. We've reached the end of the 4G cycle, and one major question facing the market centers on whether 5G will drive a new wave of handset replacements. Will anybody really want a 5G phone for new apps that are unknown today?

We think that the answer is no. We're not seeing strong demand for raw speed in the Gbps range…end users don't perceive any difference in performance above about 25 Mbps, except in very special scenarios.

IoT growth is the next variable, and while the IoT device market is exciting and growing quickly, the number of devices remains too small to make a meaningful difference in the overall RF market. In addition, the number of bands in each IoT device is much lower than the band count for smartphones, so we will need to wait for years before the IoT market makes a big impact on the RF market.

The arrival of 5G is starting to drive addition of 2-3 bands into some handset models. In general, we see these implemented with separate modules, with higher complexity to feed the 4x4 MIMO antennas. So 5G will be a positive for the RFFE market, driving an incremental uptick in RF content. The other (larger) factor in RF content growth is related to increasing band and MIMO usage in mid-tier handsets. Over the past 5 years, the mid-tier handset has migrated from about 5 bands/2x2 to about 15 bands and 4x4 MIMO, but that trend is slowing down as worldwide consumers have settled into a 'comfort zone' with their ability to communicate and roam.

Uplink MIMO and Uplink CA have some potential to add RF content to high-tier handsets. So far the numbers have been very small. We expect China Mobile, China Telecom, and China Unicom to drive adoption of higher level uplink capability, resulting in another incremental step in RF market growth.   This specific factor will be balanced by the unattractive features of UL MIMO/CA, namely, the reduced battery life could be an issue which limits adoption.

Price erosion is a significant headwind now in the market. As content growth slows down to about 10% annually, a 10% price erosion curve can offset the growth of the market, resulting in flat market performance.   That's where we are in 2019.

Premium Smartphones

Premium smartphones (phones sold for more than $500) are a clear battleground in the market. The RF dollar content in a flagship smartphone can cost roughly $23-25.   In the second half of 2019, many flagship models will incorporate 5G bands, adding a new PA/filter/switch module for one or two bands in the 3.5 GHz range in most cases.

The RF market will be influenced this year by changes in the modem lineup. Apple has abruptly changed directions. Since Apple is no longer able to rely on Intel, they have little choice but to use Qualcomm modems in their 5G models.   This gives Qualcomm a major opening to possibly break in at the RF level as well.   Whether Qualcomm succeeds or not, the increased level of competitiveness for Apple's business will result in stronger price erosion.

Similar dynamics are taking place with other flagship vendors such as Huawei and Samsung. Now that Broadcom, Skyworks, Qorvo, and Qualcomm can all support major FEM development, the level of competition will inevitably drive prices down.

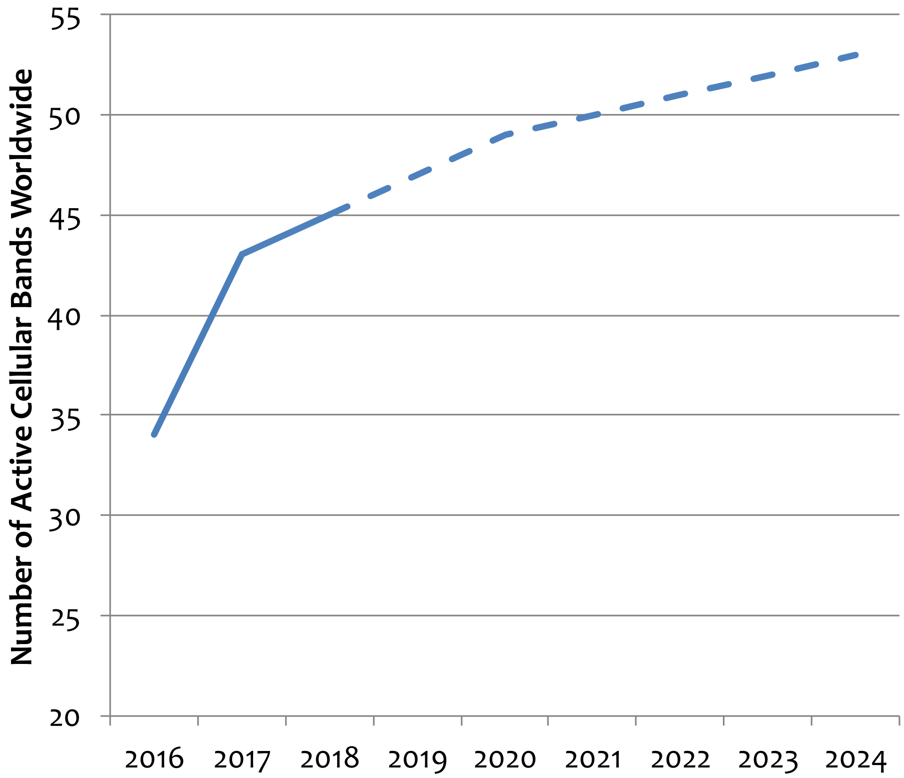


Chart 2: Number of active licensed bands used worldwide, 2016-2024

Source: Mobile Experts

Premium smartphones will be adding new bands in the 3.5 and 4.5 GHz bands as well as mm-wave bands, but the high cost and overlapping nature of these bands means that even flagship phones are likely to support selected bands and not 'all of the above'. We still don't see any phones that support all 45-50 active bands worldwide.

Mid-Tier Smartphones

The mid-tier category ($200 to $500) takes an important role in the RFFE market, as the large number of devices sold makes competition fierce. Today's mid-tier handsets have 4x4 MIMO and Carrier Aggregation, although the global single-SKU concept is generally not employed, so the number of bands tends to be lower than the global flagship models. Where the premium handsets use over 20 bands and all premium units include 4x4 MIMO, the mid-tier handsets use about 15-18 bands per handset, with less difficult CA combinations and fewer 4x4 MIMO band options. During 2019, we expect RF dollar content in this tier to be about $15.

Entry Level Smartphones

Entry-level smartphones (below $200) remain focused on cost, and therefore will minimize on RF content wherever possible. In the premium and mid-tier categories, the OEMs make choices to add bands for foreign travel, but in the entry smartphone area, only the minimum number of RF bands are covered. Even this number is increasing, as mobile operators in developing countries begin to use Carrier Aggregation in their networks. However, the distinct characteristic of the entry-level smartphone is the use of discrete components as the cheapest possible alternative, especially for handset suppliers that make only 10-15 products with production volume in the range of 10 million each.

In the entry-level tier, about 5 bands are included in each handset, for an RF dollar value in the range of $7.

Feature phones

Feature phones are still sold out there, with GSM models and simple 3G models that are surprisingly cheap. When a user only wants voice or text service, and GSM or UMTS are the only network services available, there's no point in high level operating systems or large numbers of radio bands. No MIMO. No Carrier Aggregation.

Handset suppliers have made incredible progress toward low cost here, with coverage of 3.8 bands per handset and RF dollar content below $1.00 in some cases.

Tablets and PCs

In the computing market, "Gigabit LTE" and 5G will be important features due to the more likely use of large files/downloads. Features such as 4x4 MIMO and 4-way Carrier Aggregation will also be common. Because battery power is less critical than the smartphone area, in tablets and PCs we expect higher adoption for features such as uplink MIMO and uplink Carrier Aggregation. This segment is not large enough to drive a corresponding "ecosystem" in the RF market, so a collection of modules and discrete devices are generally patched together to cover data requirements.

Because GSM and 3G are not included in most of these products, and the pressure for small size is light, the RF dollar content in the tablet/PC market is lower than the smartphone market. Roughly 3-5 bands are covered in each device, for a total of about $4-6 in RF content.

Cellular IoT Devices

We're still tracking two broad segments here: M2M refers to the old legacy formats such as GPRS and 3G, which are not optimized for battery performance. Cellular IoT refers to the newer machine communications formats which dramatically reduce current consumption, including LTE-M and NB-IoT. This market is clearly dominated by low cost devices that have very few bands (many devices only include 1-2 RF bands with very simple discrete devices or simple integration).

The typical RF content for C-IoT devices comes to roughly $1.00 or a bit less. The dollar content for NB-IoT devices in particular may drop to less than $0.40 on average in time, as we expect many NB-IoT power amplifiers to be integrated with CMOS transceivers, sacrificing output power to save on cost.

Note that Mobile Experts publishes a focused study on semiconductors for C-IoT separately, providing a great deal more detail related to modems, RF/modem integration, and vendor position in the competitive landscape. The fragmentation of the C-IoT market allows for several modem and RF vendors to survive in small niche areas, which may grow into interesting markets of their own.

Technology Changes

The premium smartphone's radio is incredibly complex and flexible, handling a huge number of modes and bands with optimized performance in many cases. For years, the RF suppliers have been simply integrating "more stuff" into the modules to keep up with MIMO and band requirements. Today, as the band growth and MIMO growth slows down, we expect technology evolution to shift.

Qualcomm, in particular, is offering more adaptive front ends that use information about the waveform to optimize performance more than ever before. In addition, Envelope Tracking for wideband 5G channels will require close coordination between modems and RF subsystems. The entry of mm-wave bands into the market will also add a new layer of RF content, which will be mostly independent of the sub-6 GHz modules.

In 2019 market, we see significant adoption of the Qualcomm 5G modem coming along, and a high attach rate of RF modules will go along with the Qualcomm lead in modems. This means that the market will be in position to use the "RF Artificial Intelligence" approach where co-design of the modem and the RFFE reaching a level where digital control will dramatically change the RF modules themselves. At the same time, uplink MIMO and uplink CA are likely to reach significant production volumes over the next year with China's ramp of 5G.

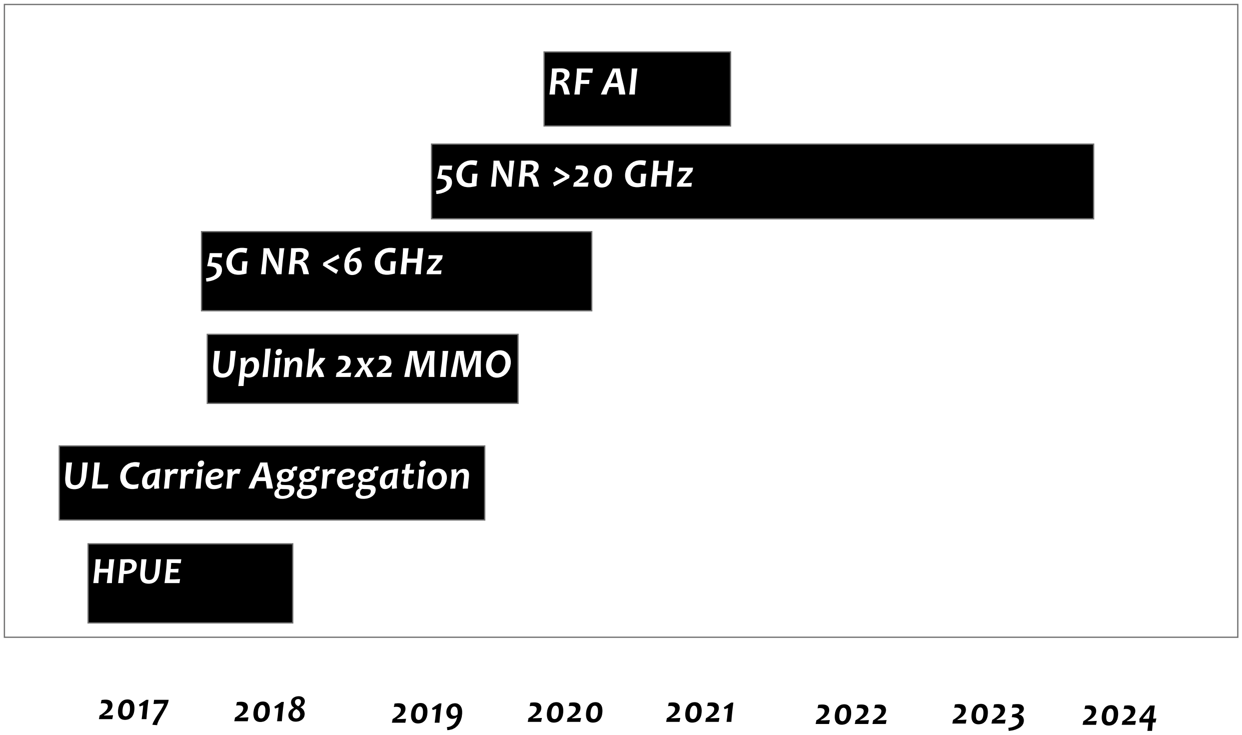


Figure 1: Timeline for New Technologies: "RF-AI", Uplink CA/MIMO, 5G, mm-waves

Source: Mobile Experts

NOTE: Boxes represent timing of technology introduction, from first production on smartphones to 10% adoption on smartphones. Introduction may be earlier for tablets/PCs (such as uplink MIMO) but this chart focuses on the smartphone segment. Note that we don't expect 10% of smartphones to adopt mm-wave by 2024, but we expect hotspots and PC applications to reach roughly 10% of smartphone volume in roughly 2024.

"RF Artificial Intelligence": With tight collaboration between modem/software engineers and RF engineers, a new opportunity has come up to improve RF performance and remove significant insertion loss/efficiency from the RFFE. If the RF front end module includes large numbers of inter-stage tuning elements with low loss, the modem can use algorithms to replace today's look-up tables with a much more flexible and effective tunable platform. One of the biggest impacts will be the ability for the RF Front End to adapt dynamically, adjusting to the actual RF channel used in multiple CA bands for the optimal compromise of linearity, filter rejection, and low loss. This process is so complex that look-up tables are not adequate; only co-design with the modem and advanced software can pull it off.

Carrier Aggregation: The benefit of CA is now clear to all mobile operators, and downlink CA is now pretty standard with 3-way and 4-way CA in premium handsets. Uplink CA is now coming to the market, especially in China where TDD networks are severely uplink limited and therefore the battery challenge of uplink CA is considered an acceptable tradeoff.

Uplink MIMO: Uplink MIMO has a direct impact on the performance of a 4G or 5G uplink in TDD networks. With the rise of 5G in China this year, we expect some adoption of UL MIMO to support the best possible uplink coverage (which is key to getting downlink coverage as well). The desire of the operator to improve UL/DL balance will be challenged by the reluctance of end users to use a handset with lower battery life. In China, the operators don't dictate which handsets the users must buy, so this feature won't be universal.

Envelope Tracking for 5G: ET technology is well established now, with multiple platforms using various forms of ET to reduce power consumption by the RFFE. The issue comes when 5G introduces bandwidths at 100 MHz and wider. At this level of bandwidth, some suppliers are not able to continue to compete, because the level of precision needed to achieve good performance is beyond a realistic manufacturing process. At wider bandwidths, we believe that adjustments by the modem (or some other digital stream) will be necessary, instead of analog tuning techniques. It's a level of system level sophistication that modem companies can deal with, but RF suppliers are not equipped to handle.

Advanced Filter Concepts: BAW filters have dominated the high-profit tier of the RFFE market for a long time, so everyone from the RF lab to Wall Street recognize BAW as a strategic technology. However, new approaches including TC-SAW, single-crystal SAW and thin-film SAW can make SAW filters perform as well as BAW or FBAR. Murata, Qualcomm/RF360, Akoustis, Resonant, and Skyworks/Panasonic have all introduced non-BAW alternatives which offer interesting performance. The challenge here is that the segment of the market requiring extreme filter performance is shifting…the new challenges are not for narrow FDD duplexers, but for wideband filters with sharp edges and possibly for tunable filter structures.

Advanced Packaging: The thin-film acoustic package (TFAP) approach represents one of the latest innovations which shrinks down the overhead to a minimum…it's basically the thickness and size of the die itself that dominates the space allocated to each filter function. In this way, a stack of 25 filters or more can be squeezed into extremely small modules.

5G below 6 GHz: At 600 MHz, 3.5 GHz, and 4.5 GHz, operators have already deployed 5G NR infrastructure. Widespread deployment has already happened in Korea and will blanket China in 2019. This means that 2019 handsets in Asia will be very focused on 5G capability. In other refarmed LTE bands below 2.3 GHz, we don't expect the 5G waveform to have a dramatic impact despite the slightly higher peak-to-average ratio (PAR). However, for wider bands in the 2.5 to 5 GHz range the channel bandwidth will have an impact on ET implementation. We expect most 5G handsets to be implemented with a separate ultra-hi band PA/filter modules in the 3-4 GHz bands without ET.

5G above 20 GHz: In the millimeter-wave bands, several huge challenges remain, such as the issue with covering antennas with a human hand. We anticipate significant device usage based on strong pressure from operators, but it might not come in the form of smartphones… watch for hotspots, CPEs, and other devices to move into mm-wave bands. The RF Front End solutions will be completely different than technologies below 6 GHz, and the vendors/integration/packaging will be completely different.

Growth Forecast

Growth has slowed down dramatically in the RFFE market. Smartphone sales have stalled, and price erosion is roughly offsetting additional RF content growth in the market.

The 5G handset market may drive new growth, as handset replacements may experience another (small) growth wave related to 5G upgrade. Currently, we don't see any new apps that justify 5G handset upgrades… but we're still waiting to see whether the lower cost per bit of 5G will drive operators to incentivize/subsidize 5G handsets.

Multiple factors contribute to ongoing growth in the mobile RF Front End market:

- 5G bands are showing up in phones now, with handsets in development that will support the 3.5 GHz and 4.9 GHz bands.
- 4x4 MIMO adoption is still growing, at least in bands above 1.5 GHz.
- Multi-band Carrier Aggregation is spreading through the operator community, making higher band count useful in mid-tier and entry-level handsets;
- Mobile operators are starting to use LAA as an additional LTE capacity boost, requiring LTE operation in the 5 GHz band. CBRS in the USA will follow in 2020.

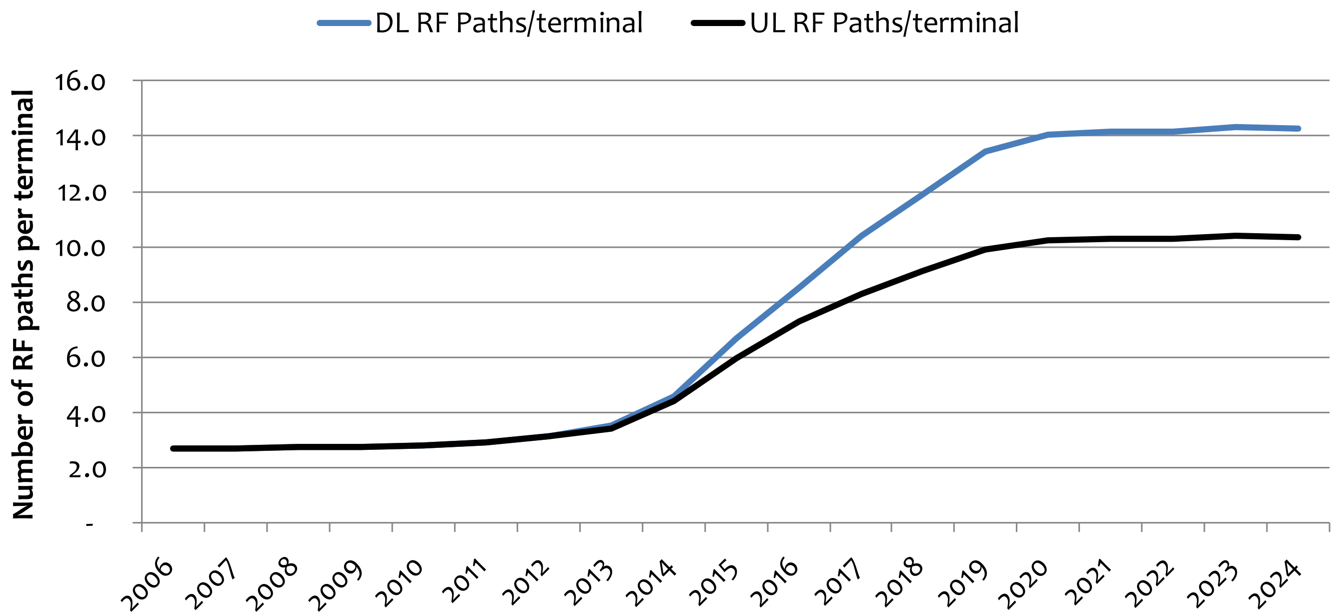


Chart 3: Number of Downlink and Uplink RF Paths per Terminal, 2006-2024

Source: Mobile Experts
NOTE: The number of RF Paths represents the number of bands and number of MIMO antennas

Due to both band growth and MIMO growth, the average number of RF downlink paths in each terminal will grow substantially, to more than 20 in the average smartphone. However, growth of IoT devices and simpler hotspots will reduce the average number of downlink RF paths per terminal in the overall market. Uplink paths will grow from 6.3 to 10 through 2024, driven by uplink MIMO and new 5G bands.

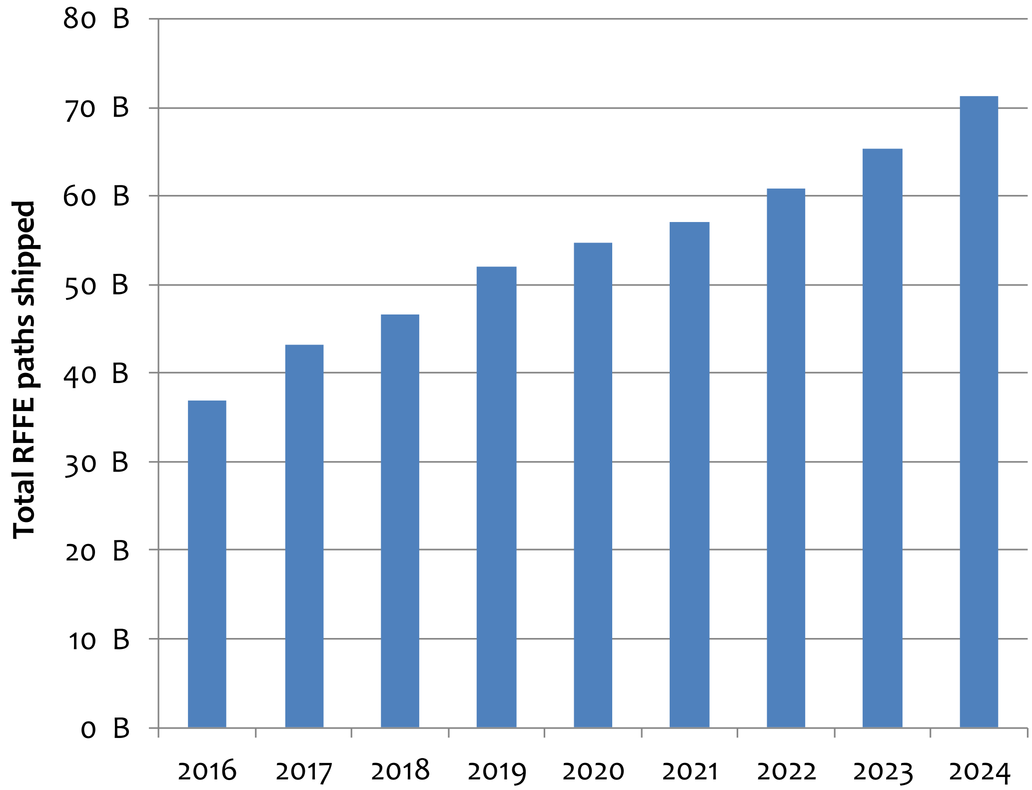


Chart 4: Total Shipments of RF paths for mobile devices, 2016-2024

Source: Mobile Experts
NOTE: The number of RF Paths represents the number of bands and number of MIMO antennas. Uplink and Downlink counted separately.

Counting uplink and downlink separately, the number of RF paths delivered to the market will grow from 37 billion in 2016 to 72 billion in 2024. (Growth is slowing down but it's still there).

The dollar content in various terminals will be fairly flat, with price erosion offsetting the growth of new bands. Millimeter wave and other features will drive some step changes here.

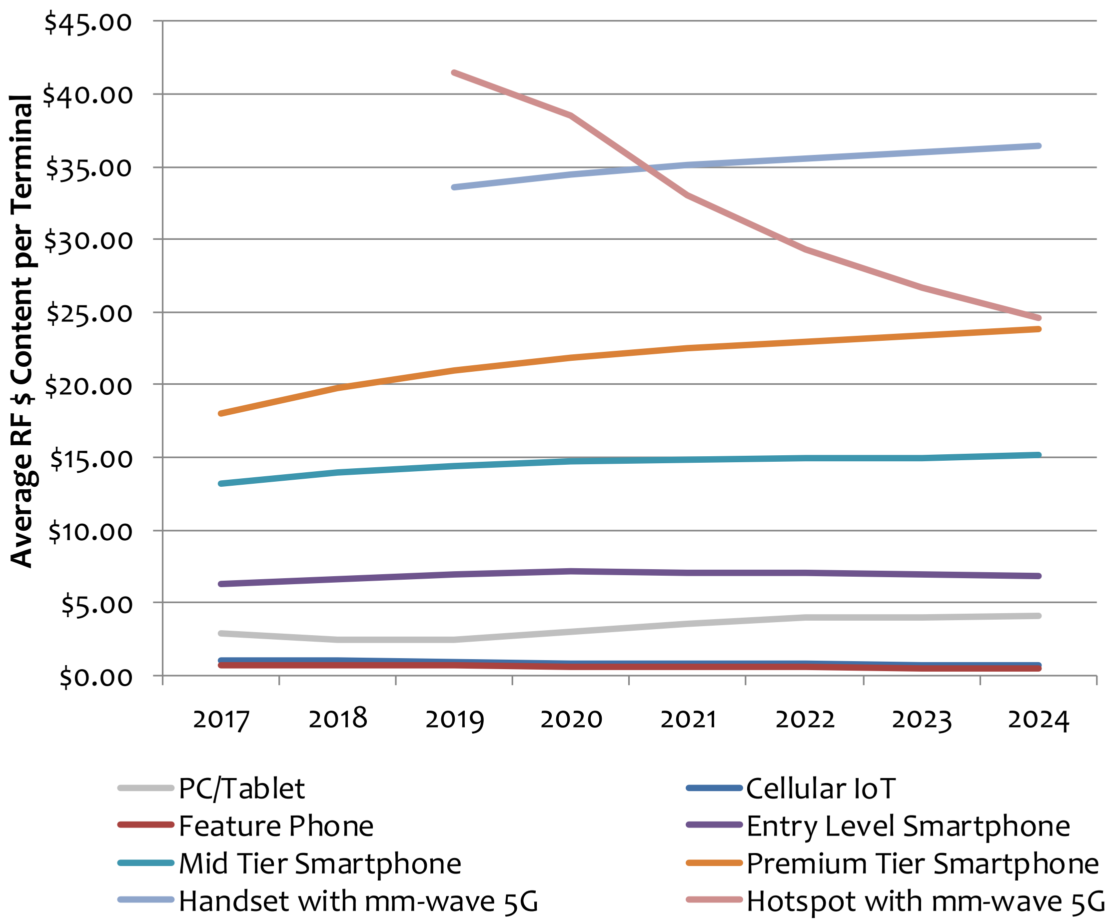


Chart 5: Dollar Content for RF Front Ends, 2017-2024

Source: Mobile Experts

What's the impact of the Huawei ban?

Recently the US Government has cut off shipments of American semiconductor components to Huawei. This move will have a dramatic impact on Huawei's smartphone business:

- Huawei uses ARM cores in their own HiSilicon processors, as well as using Qualcomm and Mediatek chips (which also use ARM cores). Both ARM and Qualcomm have signaled their compliance with the US government ban. While Huawei could defy the legal aspects and continue shipping HiSilicon processors without an ARM license, we believe that they will quickly fall behind.
- Huawei also uses Qorvo and Skyworks RF front end components extensively. As Huawei has moved into the top tier of the phone market, they have required the high-density FEM integration that only leading RF suppliers can provide. Now that

Broadcom, Qorvo, Qualcomm, and Skyworks are complying with the government ban, only Murata remains as a capable supplier for PA/filter FEM integration. (Note that Murata may have legal issues with shipments as well, to the extent that they rely on technology from their US subsidiary, pSemi).

- Huawei's entire smartphone product line relies on the Android operating system today. Without Android updates and the Google Play Store, Huawei will have a car with no wheels. One major question is hanging over Huawei's current smartphone customers: How will they get new apps in the future, as well as security and other updates for their OS? This aspect has the potential to impact new customers and also to drive existing Huawei customers to the competition.

Will Huawei's legal problems affect the overall RFFE market? It's possible that 200 million Huawei smartphones could become useless without an Android update, and we could see an upside in the RFFE market as Oppo, Vivo, Samsung, Apple, and other mid-to-high tier OEMs pick up the replacement business.

Also, we should keep in mind that Huawei has close ties to the Chinese government, and this action has sparked some intense effort to subsidize development of Chinese technology. They'll be working on their 'own' processor cores and RF front end modules. We don't expect success to be quick and easy, but with a strong national push we should expect to see Chinese semiconductor vendors emerging in roughly 2022 that have more competitive capabilities.

Market Shares

The RFFE market is starting to pinch, as several big vendors find that they can't keep growing as desired. A few small companies survive here in niche markets, but the profits are made by bigger suppliers that have strong technical differentiation and the ability to put multiple functions together in Front End Modules.

Five companies are now established as vendors with the capability to supply a complete module:

- Broadcom has a strong position in multi-function filters and high-band Front End Modules.
- Skyworks has held on to market share in Diversity Modules, Power Amplifiers, and simple FEMs based on their strong execution.
- Qorvo has moved into premium slots with BAW and PA technology that competes effectively against Broadcom in the high bands.
- Murata has all of the pieces necessary to make integrated FEMs but has not been able to convert capability into production volume. Nevertheless, Murata retains a

sizable share of the market with its strong filter capacity and low cost filter products.

- Qualcomm/RF360 (RF360 is a joint venture between Qualcomm and TDK/EPCOS) has emerged as a fifth supplier capable of major module integration and has moved into the top tier in market share during 2018.

In addition to these dominant players, a longer list of small companies survive in the fringes, mostly with discrete and single-function products such as filters or power amplifiers.

- Airoha was acquired by Mediatek during 2017 (ownership increased from 40% to 100% of shares). As a result, Airoha gets a share of PA sales to Mediatek.
- RDA is affiliated with Spreadtrum, and closely supports Transmit Modules. RDA has sampled Complete Front Ends (aka PAMiDs) with no known design wins yet.
- Huntersun supplies discrete PAs and MMPAs now, but is under pressure from their customers to move up to filter integration, which represents a difficult step for them;
- Smartermicro provides tens of millions of PA units, including multi-mode, multi-band PAs and transmit modules, and is working on some innovative FEM technologies with higher level integration of filters.
- Vanchip, Lansus, CUCT, and other Chinese PA vendors also circulate in the market with lower volumes and very low prices.
- Taiyo Yuden, Tai-Saw and WiSOL remain as stand-alone filter suppliers, mostly in the low end of the market.
- Resonant is addressing the filter market with SAW filter partners and wideband filter capability;
- Akoustis has introduced their first single-crystal filter products to the market now, directly competing with FBAR for high performance,
- Cavendish Kinetics is growing rapidly as an independent supplier of tuners and switches.

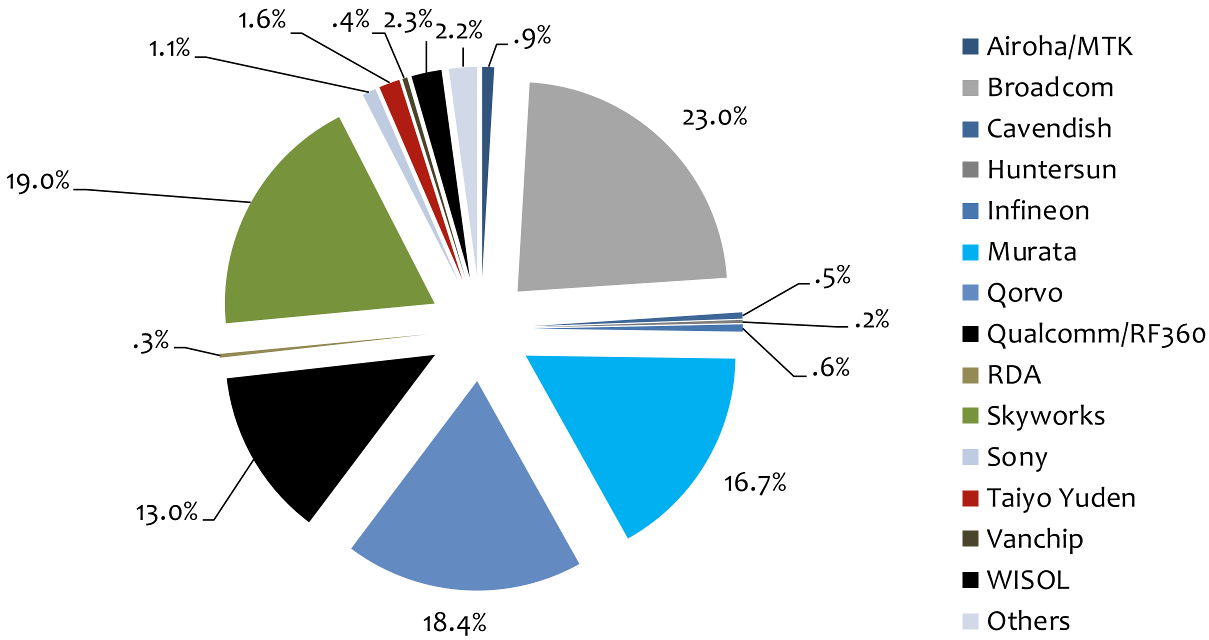


Chart 6: RF Front End Market Shares, 2018

Source: Mobile Experts NOTE: Excluding antennas and components sold at a sub-module level

3 RFFE MARKET DRIVERS

The red-hot smartphone market has cooled down, as the ninth and tenth releases of familiar platforms have run out of exciting features to drive consumer replacements. We're entering the mature phase of the market, where smartphone sales are based on simple ongoing replacement, similar to the automotive market or other mature sectors.

New growth will happen in a few areas, including mobile hotspots and IoT devices. There may also be interesting development in products such as PCs and tablets as 5G comes into play.

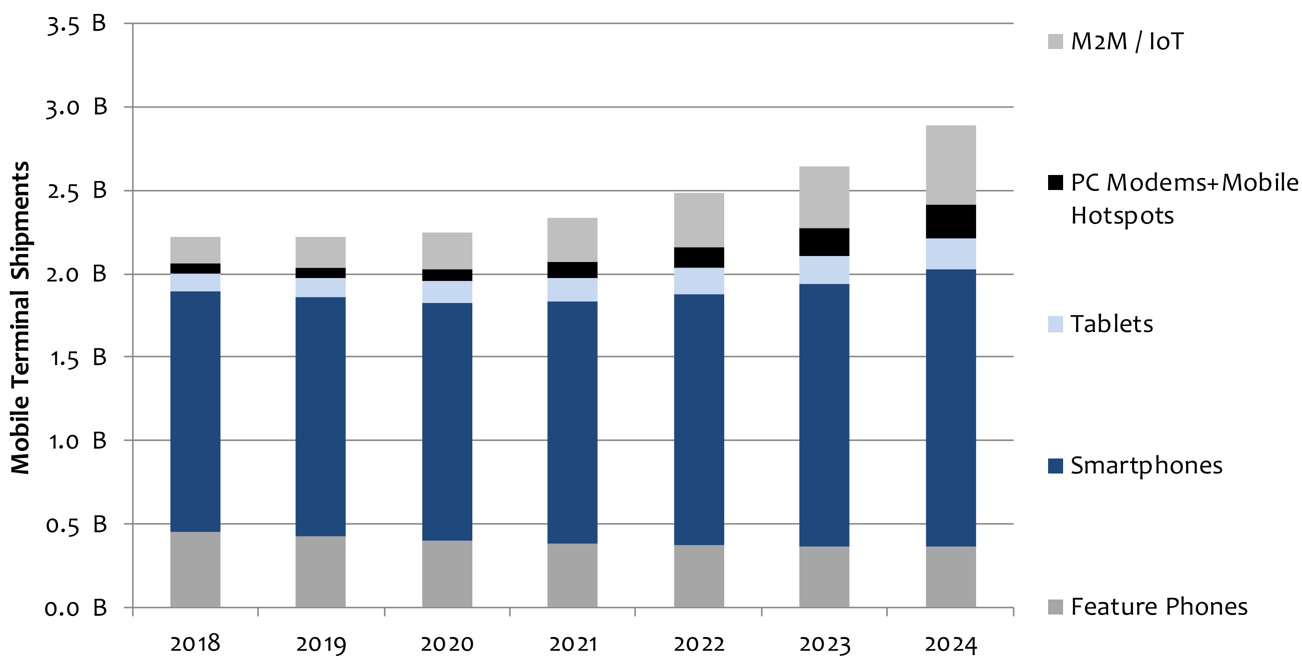


Chart 7: Forecast for Mobile Terminals, by Terminal Type, 2018-2024

Source: Mobile Experts

M2M/IoT market

For detailed coverage of the Cellular IoT market, please refer to the in-depth study published in January 2019: *Cellular IoT Devices 2019*. To summarize our findings, it's clear that LTE-M and NB-IoT device demand is growing quickly…but 5G URLLC devices will take some time before any significant quantity will be sold.

The key markets for cellular IoT devices include automotive, asset tracking, industrial IoT, and possibly healthcare.   Industrial devices represent a possible driver for 5G IoT in the future, but automation, Edge Computing, and analytics are still in development so we don't expect the 5G IoT market to turn on quickly.

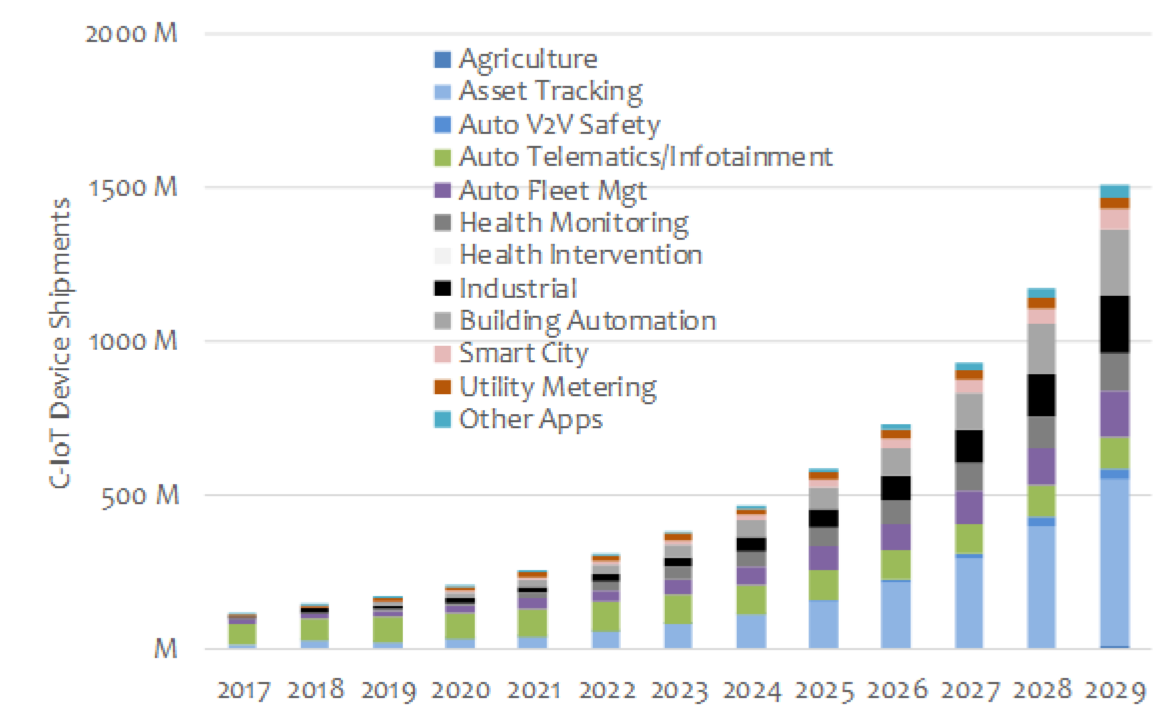


Chart 8:   Forecast for M2M/IoT Device Shipments, by application, 2017-2029

Source: Mobile Experts

The overall M2M/C-IoT forecast will grow form from 150 million units per year (2018) to about 470 million in 2024….and to 1.5 billion units by 2029.   We anticipate this slow-growth profile because in our interviews with enterprise customers, we find that utilities/industrial companies/automotive companies work on very long term development cycles.

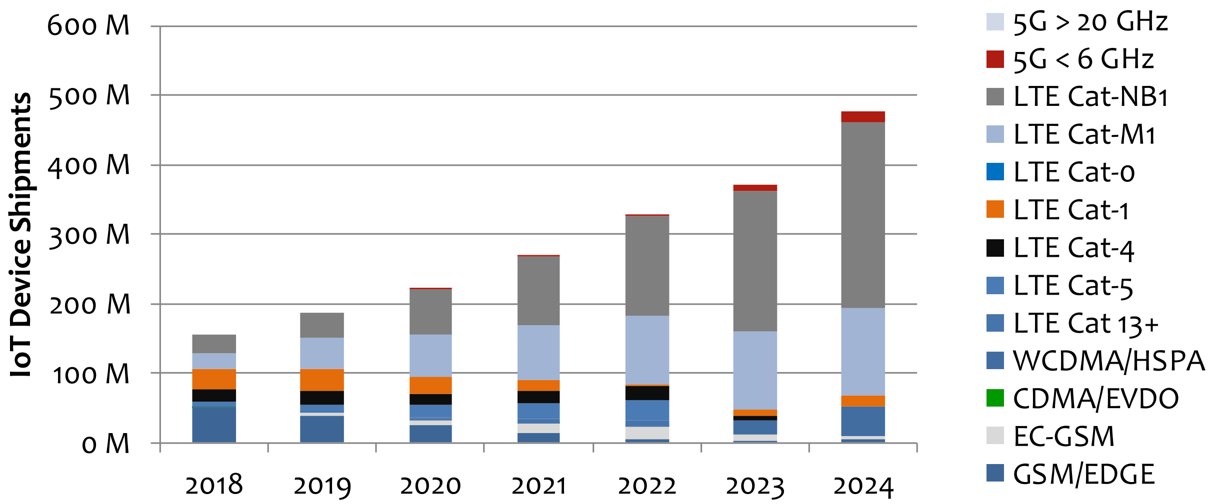


Chart 9: Forecast for M2M/IoT Device Shipments, by cellular standard, 2018-2024

Source: Mobile Experts

Carrier Aggregation Impact

Carrier Aggregation does not drive additional RF content directly. After all, this feature simply stitches together bands that are already covered by the handset, so the number of filters does not change. However, by creating a requirement to operate these bands *simultaneously*, CA drives higher dollar content in the RF chain. In particular, quadplexers, hexaplexers, and other high-value filter assemblies are becoming critical. These filter modules have become the premium components in the front end because they're difficult to make.

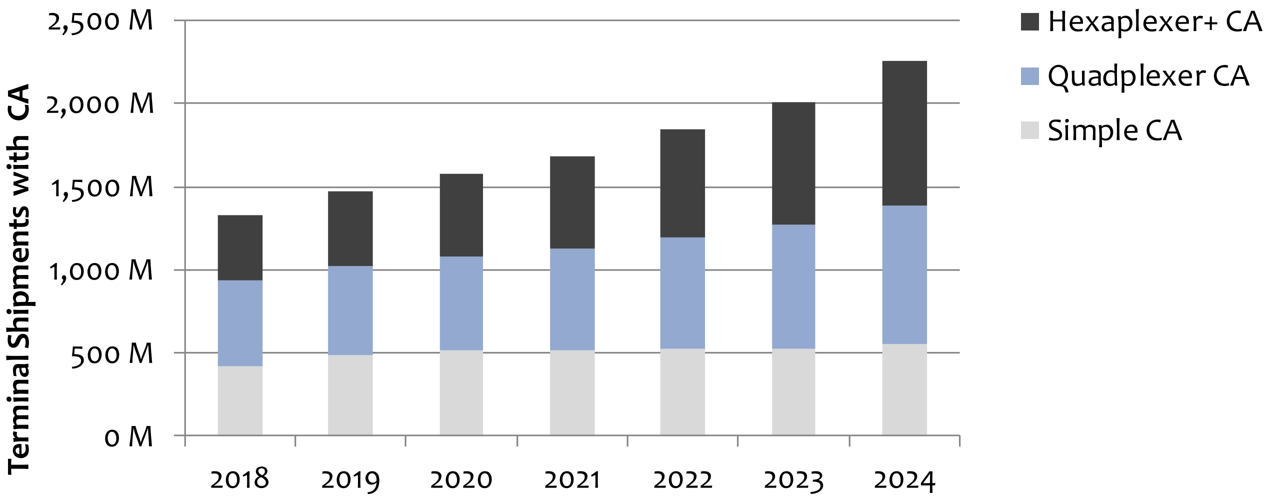


Chart 10: Handset Downlink CA Forecast, by complexity level, 2018-2024

Source: Mobile Experts.
"Quadplexer CA" refers to CA requiring four bands to be multiplexed in the same frequency group (mid-mid or low-low).
Hexaplexer+ CA refers to requirements where at least six bands must be multiplexed for simultaneous CA

Roughly speaking, downlink CA drives the use of multiplexers, which can increase the RF content in a premium smartphone by $2 overall compared with a non-CA architecture. It's not an increase in shipment volume; instead it's an increase in profitability for the few vendors that can exploit the opportunity. The driver is the emergence of mid-mid, hi-hi, and lo-lo CA combinations as operators push forward for all of their bands to be aggregated.

The most common CA use by operators happens in combinations such as Band 5/ Band 25 (low and high bands together), which does not drive any change for RF content. However, for Band 1/3 or Band 2/4 combinations, a quadplexer is required. For three-way combinations such as Band 1/3/7 or Band 25/66/30, even higher performance is required, driving a higher premium price.

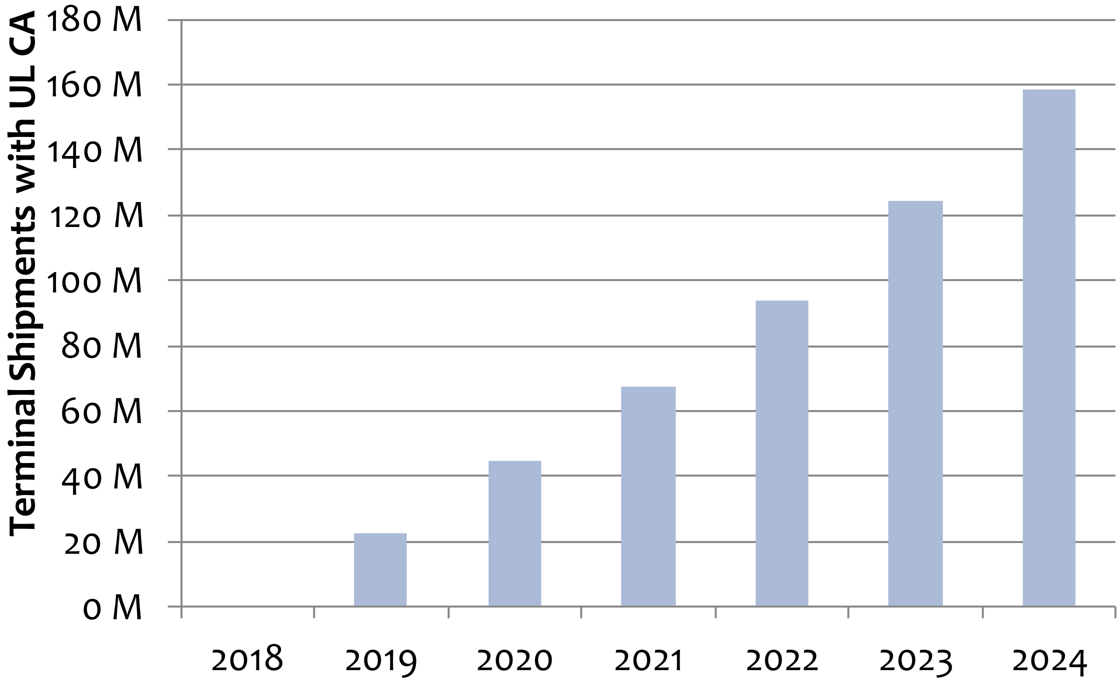


Chart 11: Handset Uplink CA Forecast, 2018-2024

Source: Mobile Experts

While downlink CA will be in most LTE handsets, uplink CA will be less common, because of technical issues such as intermodulation, battery issues, and the high cost associated with the multiple transmitters. Uplink CA has been available for some time already but we expect real adoption to begin with 2.5 GHz and 3.5 GHz 5G in China.

MIMO Impact

Almost all LTE and 5G bands above 2.3 GHz (and many in the 1.8-2.3 GHz range) will incorporate 4x4 MIMO, requiring four antennas in the terminal. The benefits are generally single-user benefits such as faster data speed and better penetration of buildings, but there are also benefits to the operator at a network level. Specifically, 4x4 MIMO improves the overall radiated efficiency of the antenna for a radio link (by having more antenna elements over a larger area), so the average signal to noise ratio for the radio link is marginally improved. This may push some users to higher coding (64QAM instead of 16QAM), which could improve capacity for the overall network.

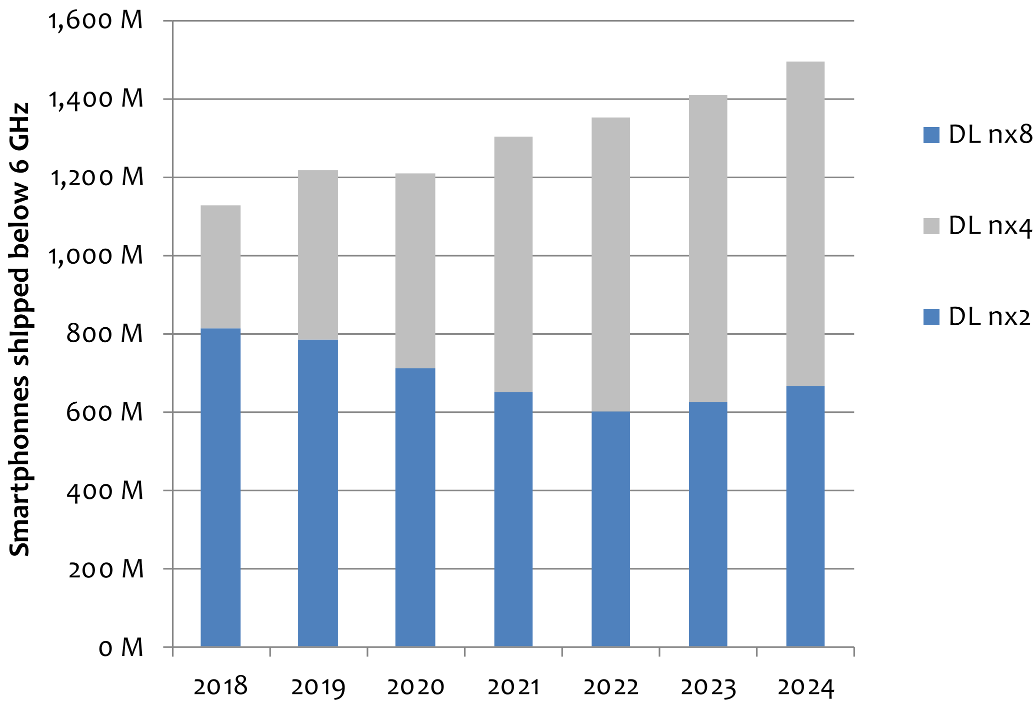


Chart 12: Smartphones Shipped with DL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz. Showing the highest MIMO level in each handset

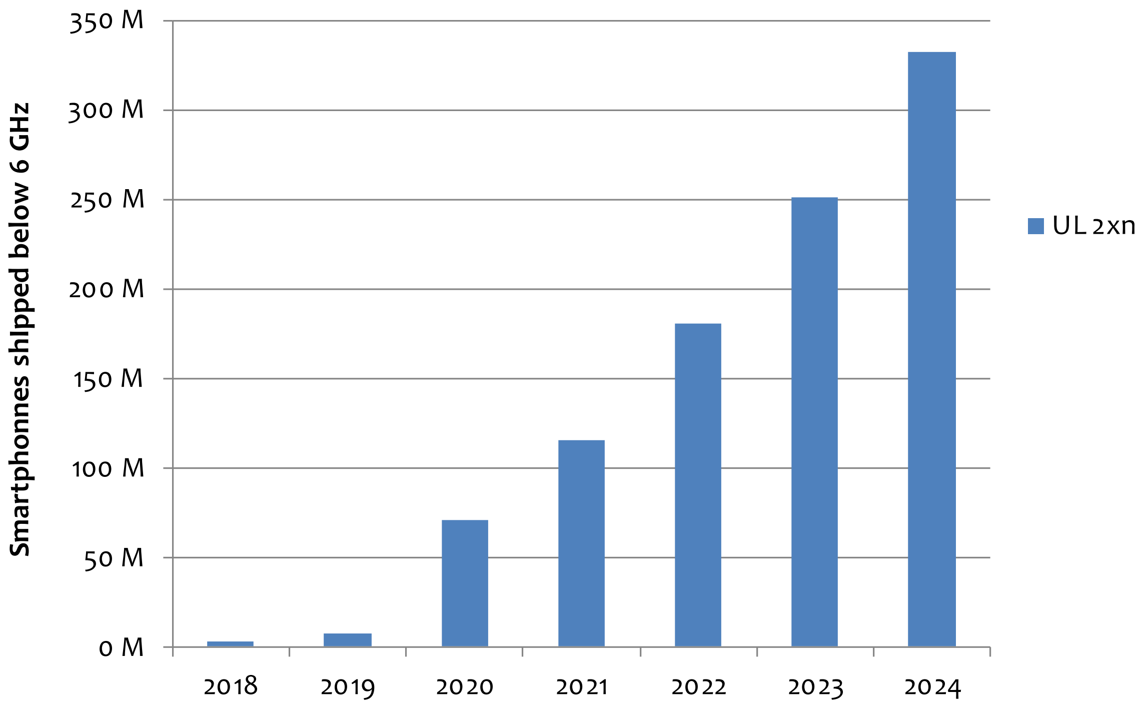


Chart 13: Smartphones Shipped with UL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

Tablets will nearly all convert to 4x4 MIMO, as size and battery constraints are relieved compared with smartphones.

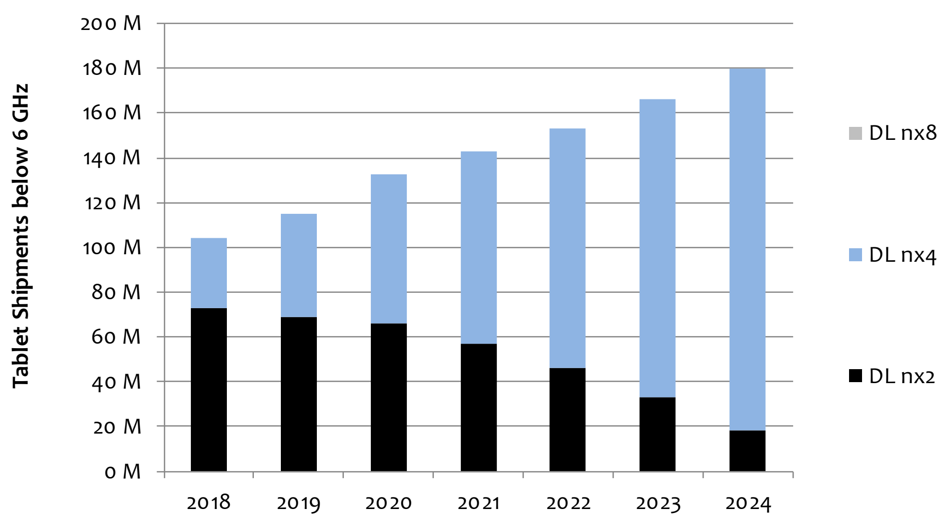


Chart 14: Tablets Shipped with DL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

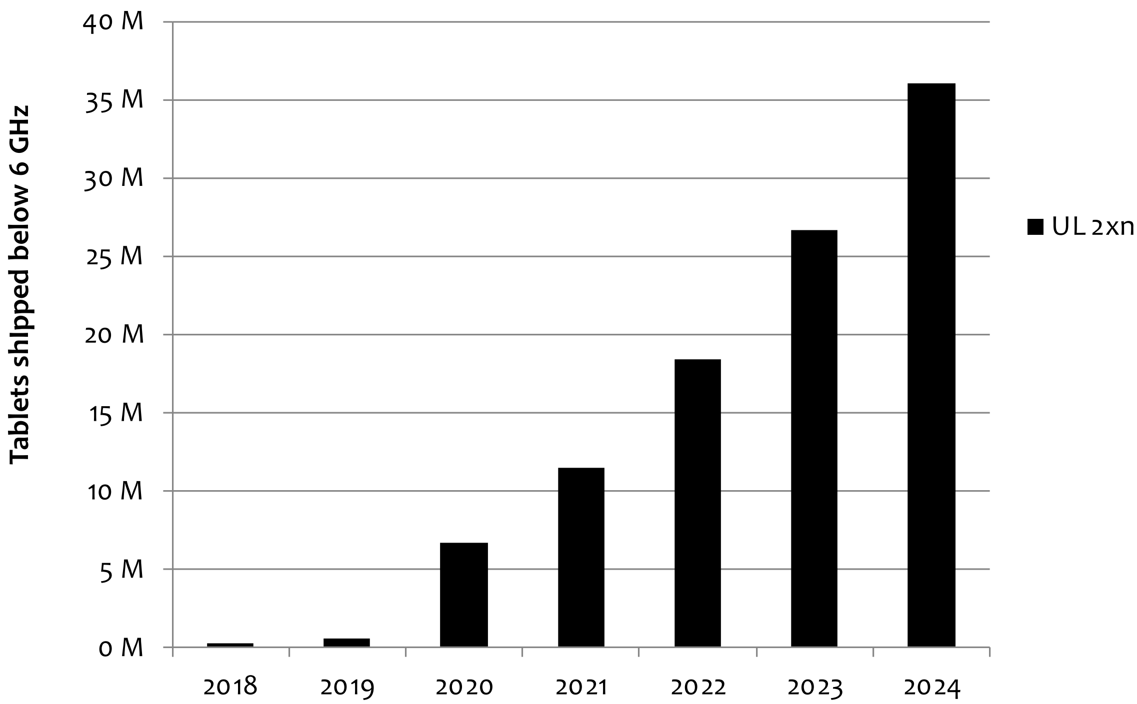


Chart 15: Tablets Shipped with UL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

PCs and mobile hotspots, as with the tablet market, will be sensitive to speed, especially as applications such as Dropbox require synchronization of huge files. We expect both uplink and downlink MIMO to be adopted heavily in this area.

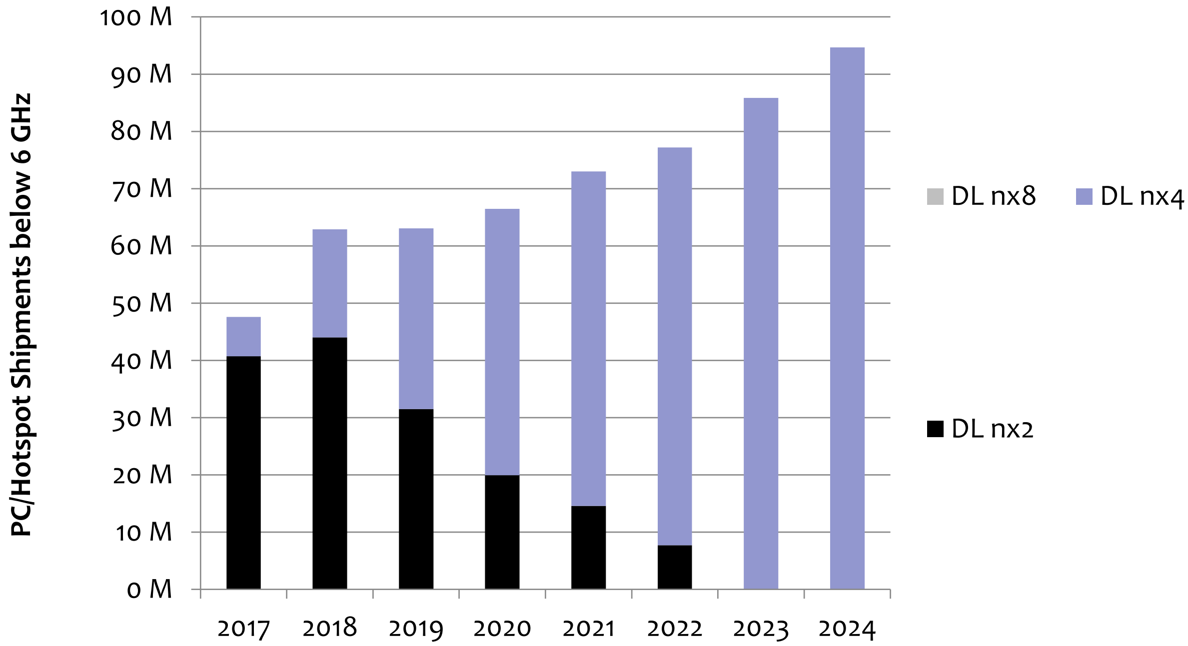


Chart 16: PCs and Hotspots Shipped with DL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

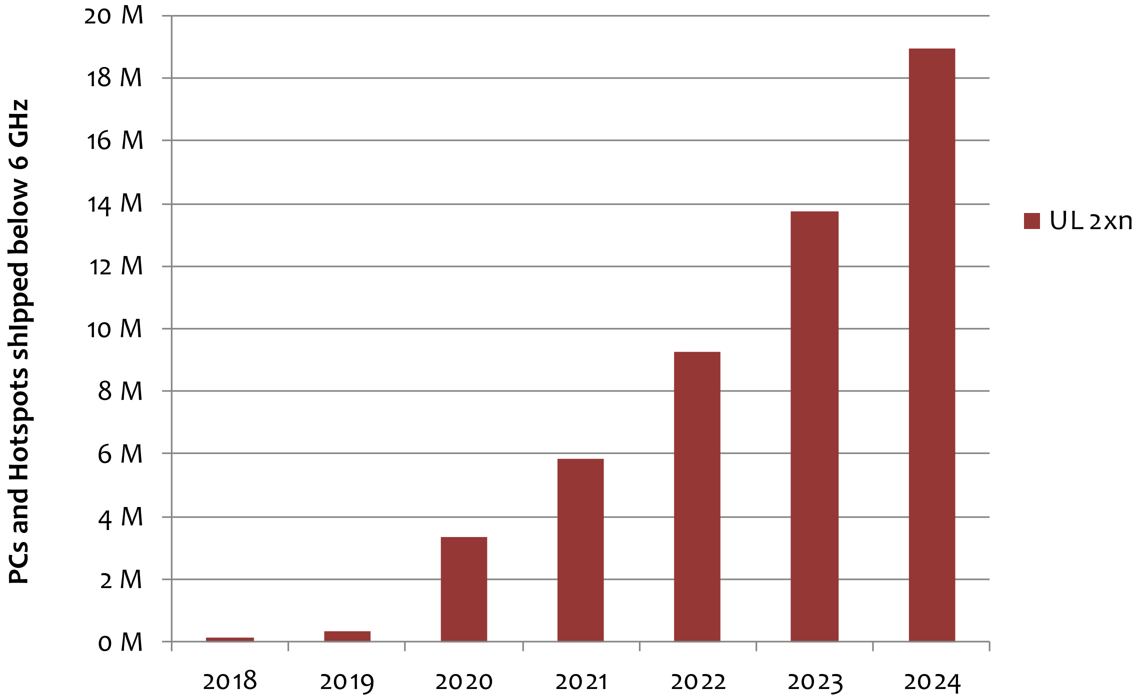


Chart 17: PCs and Hotspots Shipped with UL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

Finally, the adoption of MIMO in IoT devices will be lower..for cost reasons and because the tiny modules in IoT devices don't lend themselves to multiple antennas well. Advanced devices such as surveillance video cameras or drones need high bandwidth. A few others will use MIMO/diversity as a way to improve the link budget. In the end, we see very low adoption of uplink MIMO in IoT, and some adoption in the downlink.

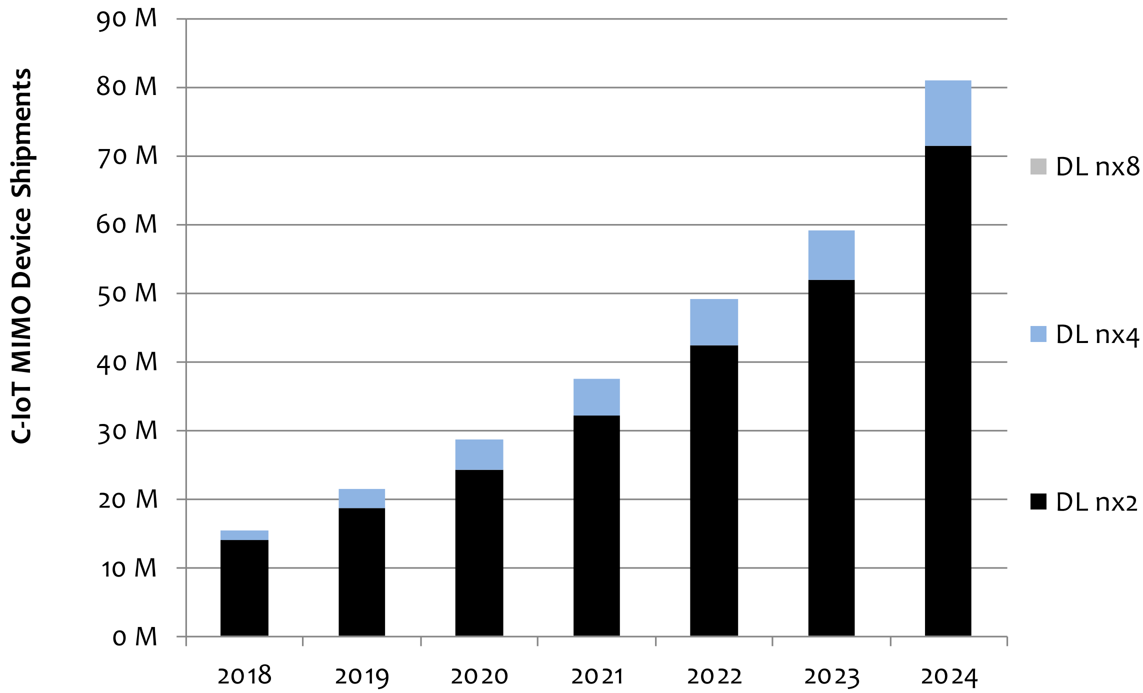


Chart 18: C-IoT Devices Shipped with DL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

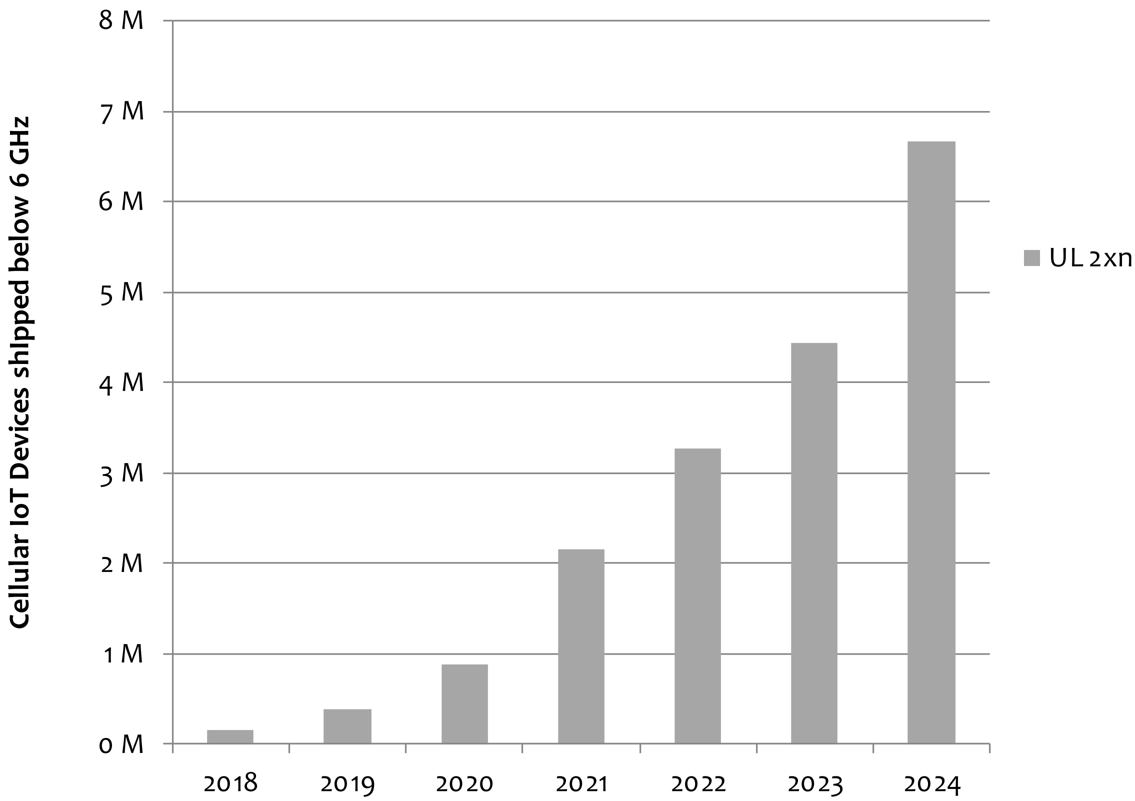


Chart 19: C-IoT Devices Shipped with UL MIMO, 2018-2024

Source: Mobile Experts
Note: Excluding RFFEs above 20 GHz

The Impact of 5G

The 5G networks have arrived about a year earlier than everyone expected in 2016, and amazingly the chipsets are also ready so that handsets and networks are hitting the market at the same time. This is the first generation where infrastructure and UEs are simultaneous.

The impact on the RF block diagram will be incremental in most cases, but dramatic in other cases. For a 2.5 GHz 5G handset, the existing FEM will be extended to wider bandwidth and will not look very different than before. Adding 3.5 GHz will mean a new module worth about $2.00. But adding 5G at 28 GHz will mean at least three sub-arrays, with dedicated space on three sides of the terminal, and three up/downconverter modules to allow for IF transport on the PC board inside the terminal.

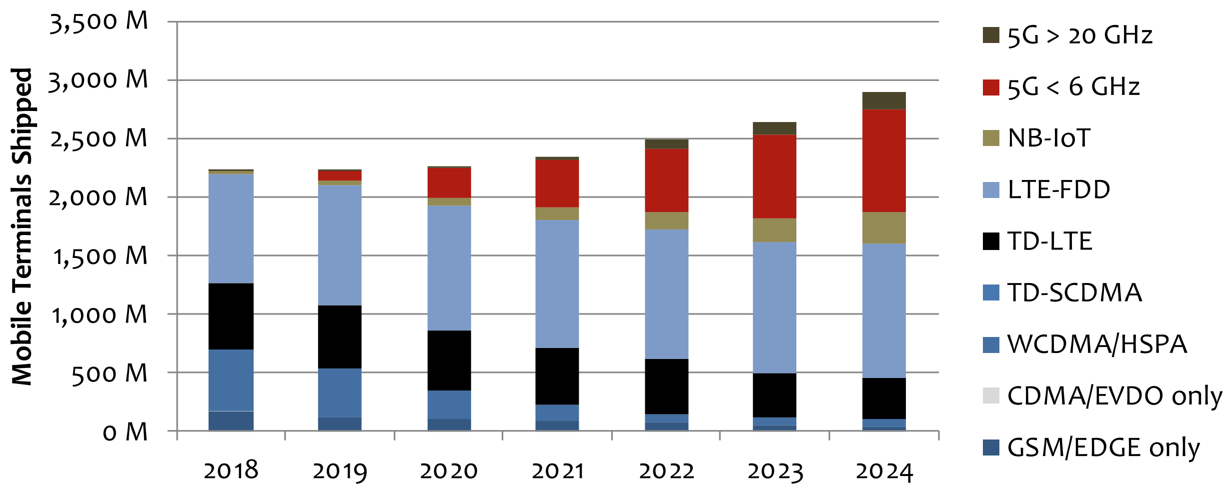


Chart 20: Mobile Terminal Forecast, by Air Interface, 2018-2024

Source: Mobile Experts. NOTE: Multimode terminals are listed by the highest air interface standard included.

From a market size point of view, the biggest impact of 5G will be the value of the ultra-high band FEM. We anticipate roughly 950 million FEMs for the 3-6 GHz bands in 2024, representing about $1B in revenue. Another major impact will be the bandwidth of Envelope Tracking… wider bandwidths of 100 MHz or more will drive the OEMs to use a carefully selected modem/RF combination, giving Qualcomm an advantage and blocking some vendors out altogether.

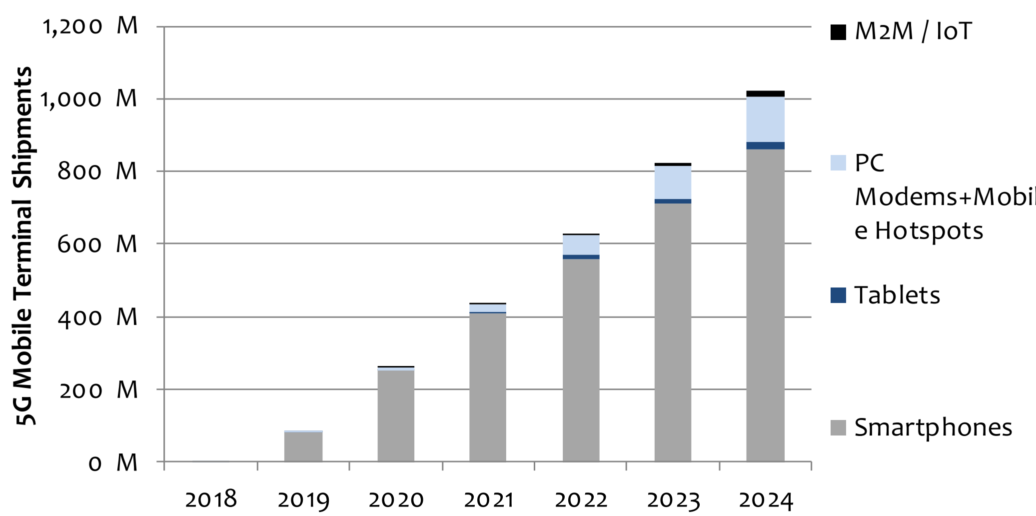


Chart 21: 5G Mobile Terminal Forecast, by terminal type, 2018-2024

Source: Mobile Experts

The Impact of LAA, LTE-U and CBRS

License-assisted Access (LAA) is an important feature to the mobile operators because it provides capacity on 'free' spectrum, augmenting the total capacity of the network at a very low cost. Small cell infrastructure with LAA capability is now well underway, and we expect this feature to be increasingly required in handsets that support key operators.

OEMs will step up to add LAA on top of the existing Wi-Fi support and other bands (n77, n78, n79 at 3.5 GHz), so the impact will be a series of filters, switches, and general plumbing complexity for 4x4 MIMO in the ultra-high bands.

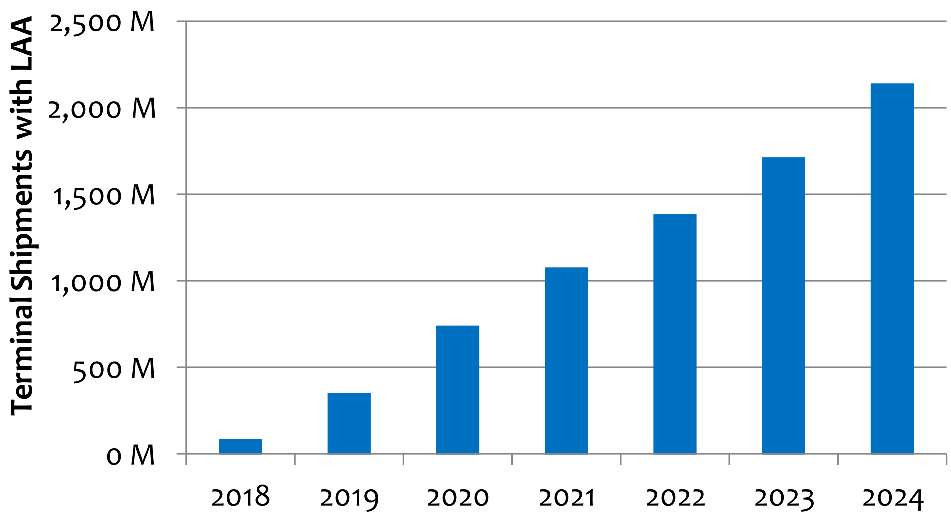


Chart 22: Mobile Terminal Shipments with LAA, 2018-2024

Source: Mobile Experts

4 KEY TECHNOLOGY BACKGROUND

New bands and features keep coming, driving the RF suppliers to continually shrink the space for each RF function and add completely new bands/modes to the terminal.

This year, we're tracking three key technology initiatives:

- Millimeter wave radios for 5G;
- Envelope Tracking for >100 MHz bandwidth;
- RFFE Tuning at a sub-component level; and
- Uplink MIMO.

Millimeter Wave 5G Networks

Many people are mystified with regard to 5G mm-wave radios in a phone. After all, who really needs 2 Gbps in their phone, even for VR or other speculative apps? What's the battery impact (and heat impact) if such a high speed is actually used?

It doesn't make a lot of sense from the handset point of view. To understand the rationale for 5G mm-wave, we offer a network point of view. The mobile operators desperately want to use 5G mm-wave capacity in the network, because they're running out of capacity to serve millions of people below 6 GHz.

Mobile Experts modeled the capacity of some key LTE networks, to understand exactly WHERE and WHEN the operators will need mm-wave capacity. In the cases of AT&T and Verizon (as well as operators in Korea, Japan, Finland, and a few other countries) the situation is immediate. Our analysis indicates that AT&T and Verizon will add capacity using Small Cells, LAA, and CBRS in the near term to keep up with demand. By aggressively adding small cells that include all possible bands below 6 GHz, Verizon and AT&T can add significant capacity but will not quite keep up with demand growth. The addition of the 3.7 GHz band will bring a bit more capacity in 2023-2026, but even a rapid deployment will not keep up with capacity nationwide.

Verizon, AT&T, SKT, NTT DoCoMo, and other operators have already been adding small cells as rapidly as their lawyers can gain access to poles. The limitation here is not exactly technical, it's a challenge to equip new sites quickly enough to keep up with demand, especially with small cells that use skinny bands below 6 GHz.

This means that hotspots in the cities will experience overloading throughout the 2022-2026 timeframe….mm-wave capacity will become *absolutely necessary* for locations such as subway platforms, stadiums, and other crowded spots where the traffic peaks, as well as dense urban housing centers where fixed broadband traffic is heavy today. Millimeter-wave base stations will be indispensable for mobile capacity starting in 3 years. A detailed and complete review of various urban/suburban/rural scenarios was published in our recent 5G Broadband Business Case (MEXP-5GBB-18-BC) report.

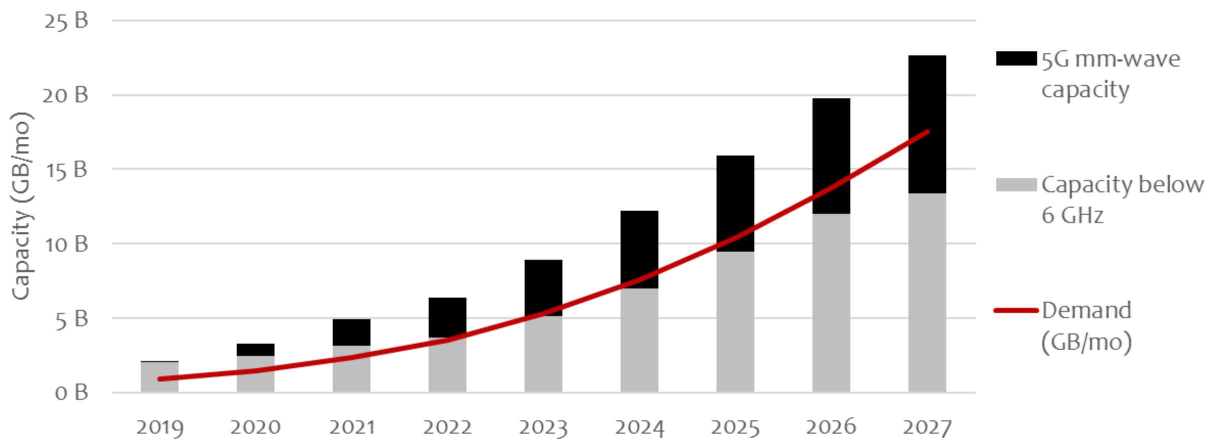


Chart 23: Mobile Demand vs Mobile Network Capacity, 2019-2027 (USA Urban Scenario)

Source: Mobile Experts

What does this mean? We should not think about 5G mm-wave as a cool feature to have in a phone. Consumers won't care about it because most consumers don't really want to pay more for speeds above 200 Mbps, which they can get with bands below 6 GHz.

Instead, we should think about mm-wave as a feature that operators want to drive into the smartphone, because the operators need the capacity. So, operators will subsidize a 5G mm-wave terminal, or even give away free hotspots, to move traffic from low bands to mm-wave bands.

For this reason, we don't believe that 5G mm-wave will necessarily happen in smartphones. We think that operators are more likely to give away hotspots, which are cheaper than the latest $1500+ smartphones. In our forecast, we've modeled the mm-wave growth as a hotspot phenomenon. We could be wrong about this, and we will be watching the operators to see whether they subsidize hotspots or handsets for mm-wave offloading.

Digitization and "RF Artificial Intelligence"

The complexity of tuning an RFFE for multiple CA bands, multiple MIMO states, and a wide range of power levels has become a major challenge for the engineer. The traditional approach is to use look-up tables for each dimension (power level, CA status, MIMO status) and set a static configuration for the RFFE to support the desired output.

That approach is changing, as RF vendors create a large number of adjustment points within each amplifier, and even for elements within filters. It may not even be cost-effective to fully characterize every possible setting for large numbers of tuning elements, for every power level, frequency, and temperature. We're using the term "RF Artificial Intelligence" to indicate that the modem will take a more active role in making decisions about optimal settings, instead of simply using look-up tables.

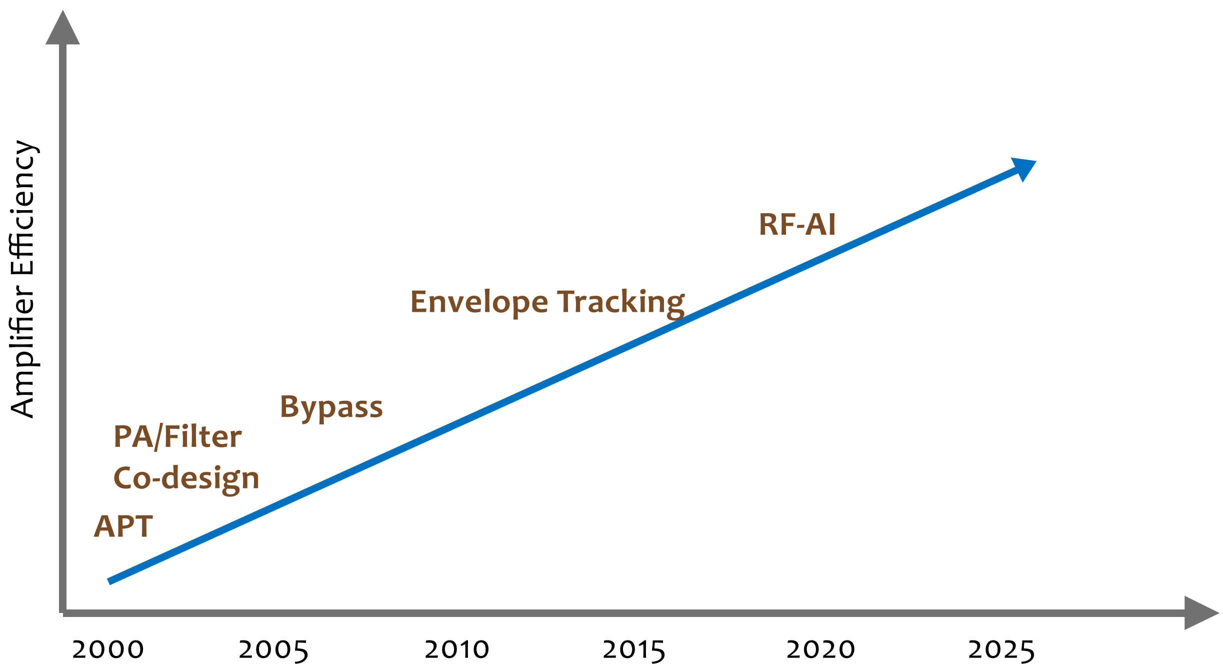


Figure 2: Efficiency impact of Digital Control for the RFFE

Source: Mobile Experts

The impact could be significant. We presented some conceptual information last year, and we're showing some of the illustrations again here. No new public information has been released that we can report, but we have been able to verify recently that this approach works and has significant battery life savings. Our previous estimate of roughly 20% battery power savings appears to be accurate so far.

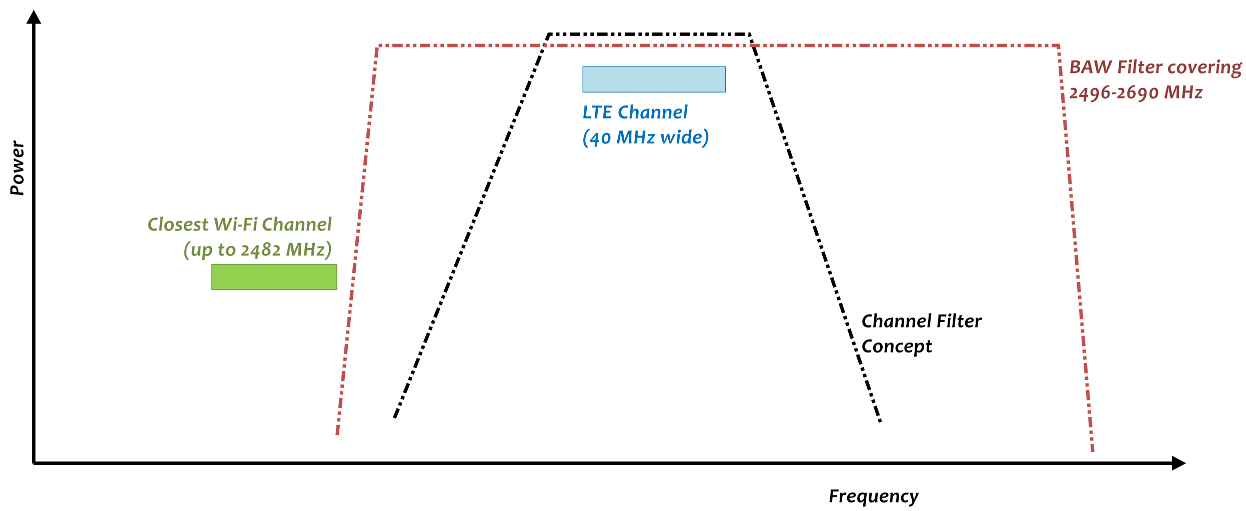


Figure 3: The Channel Filter concept vs. Band Filter concept

Source: Mobile Experts

One major change in this approach could be the use of "Channel Filters" instead of "Band Filters". For the past 30 years, filters have been sold as static components, without the ability to adjust for the actual RF signals. With aggressive use of tuning, and knowledge about the actual RF signal being used, the modem can control the filter to pass a narrower band, thus relaxing the skirt requirements.

We believe that this approach, if combined with thin-film SAW or other monolithic integration, could open up a new level of performance. The Wi-Fi coexistence filter is one example, where the actual LTE channel is rarely set up in close proximity to the actual Wi-Fi channel. In this case, clever use of tuning can reconfigure the filter for best performance in the actual LTE channel, providing high rejection for the Wi-Fi channel with very low loss for the actual LTE channel in play.

This concept is not new, but for many years has not been implemented because the loss of the tuning elements would create higher insertion loss than the filter can allow. Handset OEMs are starting to investigate this idea, and we've heard that new filter techniques may facilitate to this kind of tuning in new ways. If it is proven, then the impact could be dramatic.

We believe that this approach will be limited, at least at first, to simpler FEMs that do not include high-level Carrier Aggregation. Combining this approach with high-performance multiplexers could be a difficult challenge, so we anticipate the best use of this technique could be in a few specific areas:

- Uplink MIMO FEMs that require transmit capability only in one or two bands, but require several TDD bands for diversity reception.
- Low-band CFEs that do not require a quadplexer.
- 5G FEMs that cover wide bands with Envelope Tracking and can benefit from advanced calibration (but may not need anything special on the filter side).

One major point here: Success in this “RF Artificial Intelligence” involves two major elements: clever algorithms in the modem to “learn” how to optimize the RFFE, and very tight integration of RF components with large numbers of inter-stage tuning elements used in multiple ways. Both elements are necessary to success, and the level of coordination between these two development areas must be very intimate.

The major challenges of “RF AI” involve the intimate level of coordination needed between modem engineers and RF engineers. Even within one company this can be very difficult, and during 2019 it appears to have stalled one major project. The next challenge will be to gain acceptance by the market for cases that are not fully tested. After all, how do you test something that is constantly optimizing to unique channel bandwidth/waveform parameters? The timeframe needed for OEMs and government regulators to accept this approach is currently unknown.

Impact of Uplink MIMO

Uplink MIMO has the potential to dramatically increase the numbers of FEMs used in the RFFE. It’s an expensive decision, potentially adding $2 to the handset’s RF section, and it certainly will draw more battery power. So why are we doing this?

The operators have a problem with TDD-based communications in the 2-6 GHz range, where the downlink is much stronger than the uplink. In China, at 2.5 GHz today’s LTE users can experience a link budget imbalance where the downlink is 10-12 dB better than the uplink. This means that downlink capacity is fine, but whenever the users walk into a building the closed-loop communications will drop and the downlink capacity is useless.

To compensate, mobile operators have pushed for HPUE (boosting power in the uplink by 3 dB), and that feature has been generally adopted. The next step is to add Uplink MIMO, essentially doubling the power and effective radiated power again.

Some industry experts have predicted that this feature will double the use of all PAMiDs, but we don’t see it that way. Instead we believe that Uplink MIMO will only be used in the TDD bands above 2 GHz, so there’s no need to duplicate the low-band modules. In fact, we expect that when the modules are optimized, the secondary FEMs in the 2.3-2.5 GHz band and the 3-5 GHz band will be simplified to handle only one or two bands each.

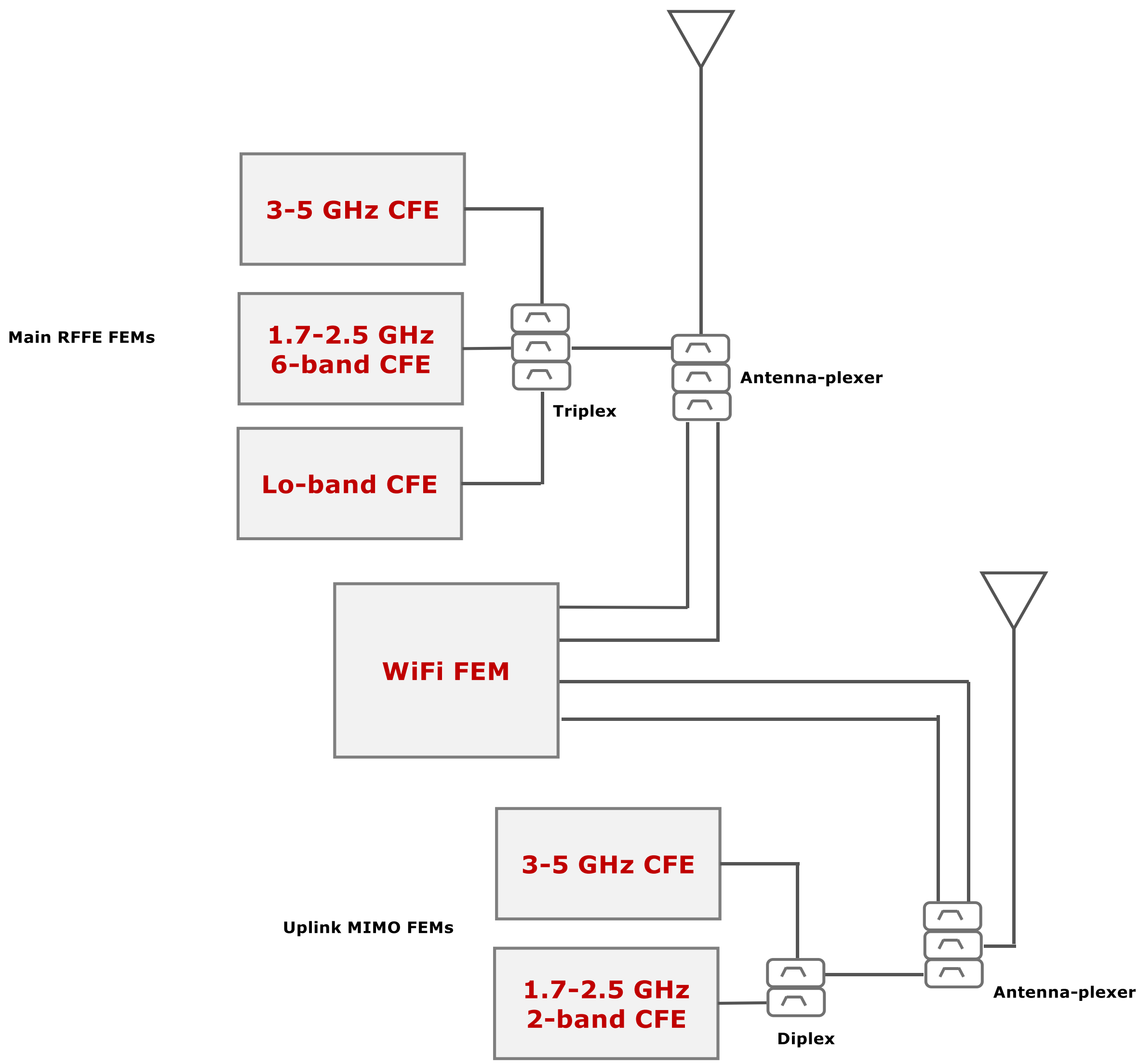


Figure 4: 5G smartphone block diagram with Uplink MIMO

Source: Mobile Experts

Advanced Packaging

Over the past ten years, the size of the package surrounding a typical acoustic filter has shrunk enormously. The innovative flip-chip approaches of the 2000s gave way to die-sized package approaches (DSSP is the Qualcomm/EPCOS name for this), eliminating the cover and frame which provided protection and stability. As multi-chip modules become the primary aspect of the market, die are now stacked in three dimensions, making the height of each function critical. The most recent packaging of bare die-sized products have extremely low overhead in terms of packaging height, with a profile of less than 200 microns (0.2 mm) for each acoustic filter. In this way, 15-20 filters can be packaged together in a tiny diversity module or in tight places within a CFE.

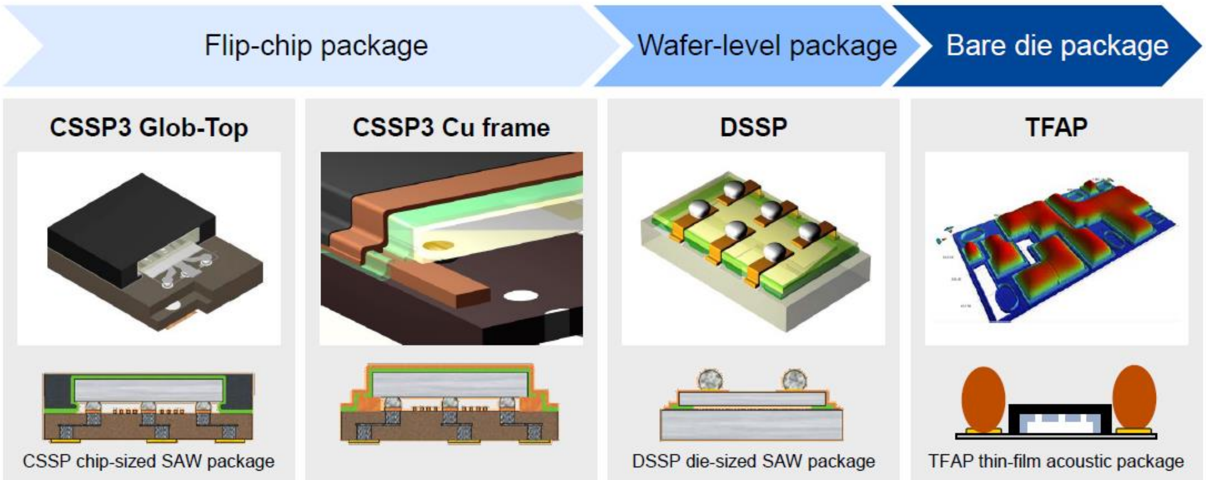


Figure 5: Evolution in packaging of acoustic filters

Source: RF360

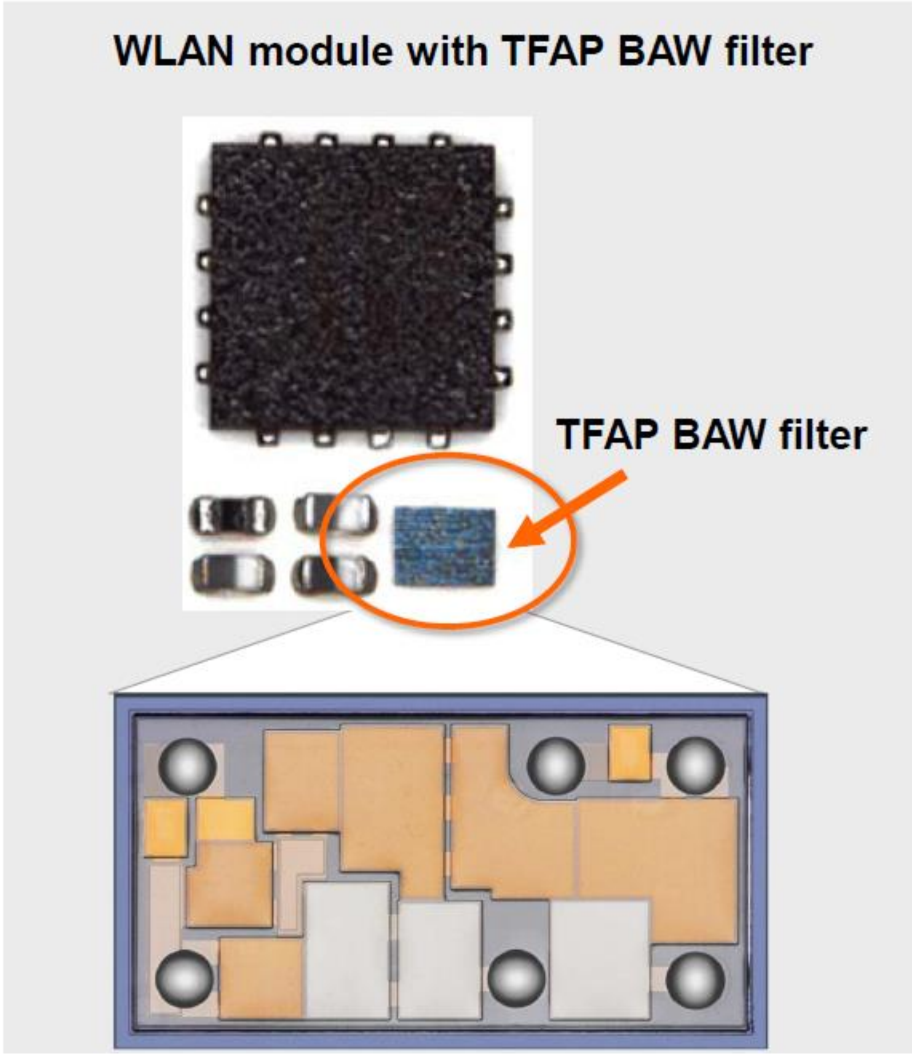


Figure 6: RF360 example of advanced filter packaging

Source: RF360

Wideband Filters

As 5G comes into the handset market, the initial implementation will involve multiple PA/filter modules that address specific bands: n77, n78, n79. Roughly 200-300 MHz bandwidth for these bandpass filters will be used in the early implementation. But this approach requires multiple modules for the various bands in the 3.3 GHz to 4.2 GHz range.

A few companies have developed methods to extend bandwidth while achieving high rejection in the nearby unlicensed bands. Resonant and Akoustis are two start-up companies with good ideas geared toward extending bandwidth into the 600 MHz range, or even wider, to simplify the high-band front end.

In the 3.5 GHz range, the big challenge is wide bandwidth while maintaining good wideband performance and sharp enough cutoff. At 4.8-4.9 GHz, the challenge gets more extreme as coexistence with the unlicensed bands above 5 GHz gets very narrow, and the raw performance of the resonators will be important.

It's too early for us to determine whether FBAR or BAW technology will achieve the performance required by smartphone OEMs. Early implementation in handsets will be with filters only 200 MHz wide, so the competition will play out over the next two years.

Piezo-on-Insulator (POI or Thin-Film SAW)

Silicon-on-insulator technology has provided a very useful, high-linearity process with an ability to integrate RF CMOS with other functions seamlessly. Today, some filter vendors are experimenting with Piezo-on-Insulator material, where single-crystal piezoelectric material (such as $LiTaO_3$) l is deposited on top of an oxide, on high resistivity silicon. Murata calls this "IHP" and others call it "thin-film SAW".

	SAW	TC-SAW	BAW	Single Crystal BAW	TF-SAW
Multiple Frequency Integration	Difficult	Difficult	Difficult	Difficult	Easier
Q	1500	1500	4000	8000?	5000
TCF	40 ppm/C	20 ppm/C	20 ppm/C		5 ppm/C
$k^2_{effective}$	7%	7%	7%	14%	12%
Integration with CMOS	No	No	No	No	Possible

Figure 7: Comparison of filter technologies for raw performance

Source: SOITEC

POI technology has the potential to improve coupling factor ($k^2_{effective}$), as well as temperature drift and possibly the quality factor (Q) of the resonators. This combination of variables means that the POI technology could possibly upset FBAR/BAW in terms of performance in highly complex filter assemblies, with very good performance in surface-wave mode. The high $k^2_{effective}$ in particular may be important with the new high-bandwidth opportunities for 5G filters.

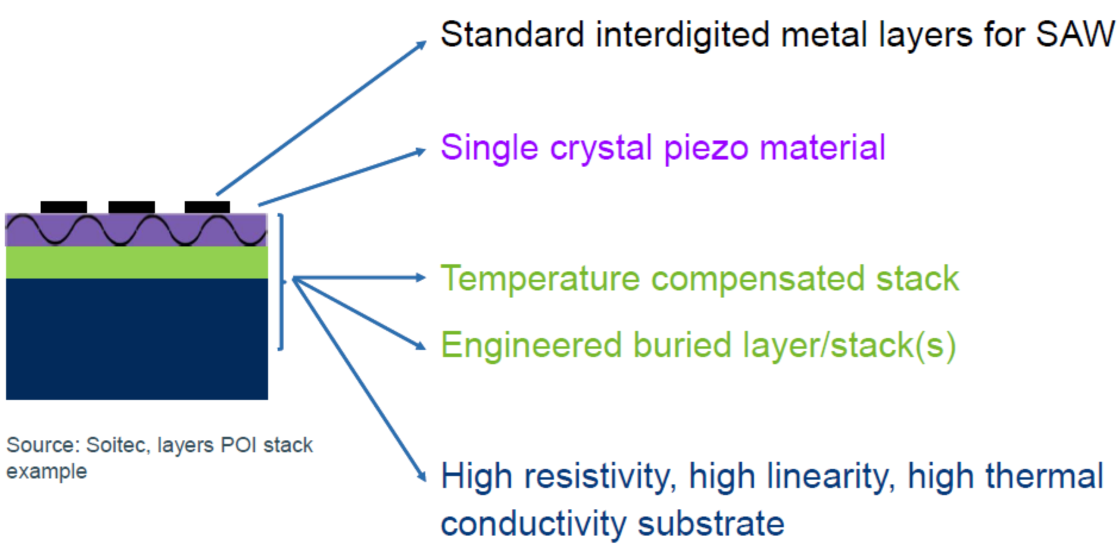


Figure 8: Cross section showing POI concept

Source: SOITEC

More importantly, the POI process has the potential for integration of active elements with filter elements on the same wafer. This could open up a new level of control in the RF front end.

Expected Block Diagrams for iPhone and Galaxy S11

The flagship smartphone platforms will be updated over the next year to include 5G in the 2.5 to 4.9 GHz bands. In general, this change will be an incremental improvement, with most of the RF front end components remaining the same but adding new modules for the "ultra-high band".

One change will be that Band 41 (2.5 GHz) will be grouped together with 3.5 and 4.5 GHz as part of a wideband 5G front end, instead of the narrowband FEMs serving the traditional LTE channels.

For a 5G version of iPhone, we have some conflicting inputs. One view is that Apple will use a single module for the 5G bands at 2.5 or 3.5 GHz, and will serve the need for the Sounding Reference Signal (SRS) by including a transfer switch and a transmission line to carry the 5G uplink signal to the opposite end of the phone. This configuration can have significant insertion loss, plus a costly transmission line.

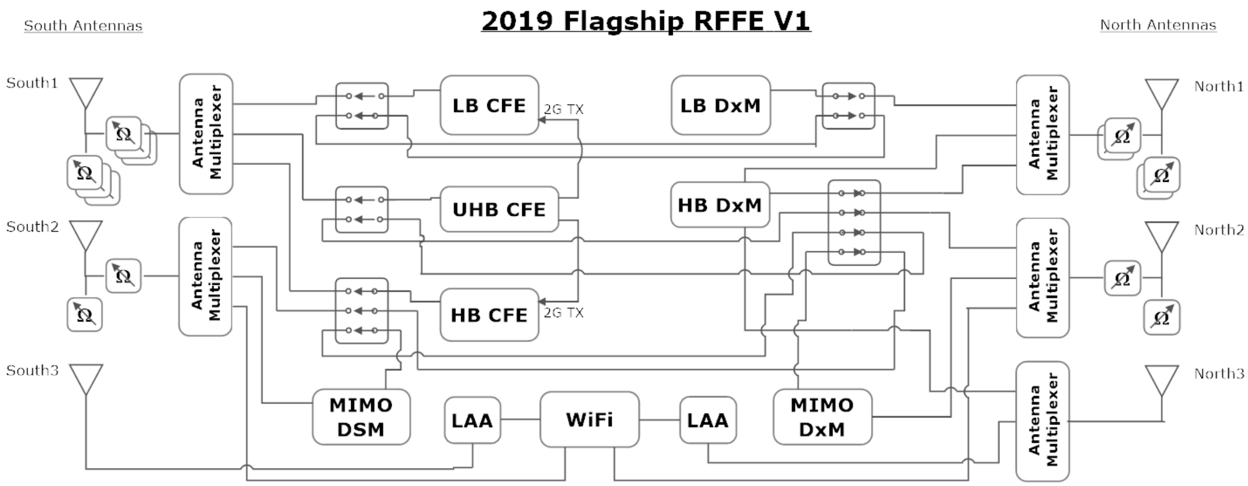


Figure 9: One possible configuration for an upcoming 5G Apple iPhone

Source: Mobile Experts.. (Note that in our diagrams we use the terminology for the "North" end of the smartphone and the "South" end of the smartphone to avoid confusion between "Upper" and "Lower" frequencies.)

Another alternative for Apple will be to add a second uplink FEM into the 5G iPhone. This approach reduces the loss in the secondary transmit configuration, as well as providing the possibility of uplink MIMO.

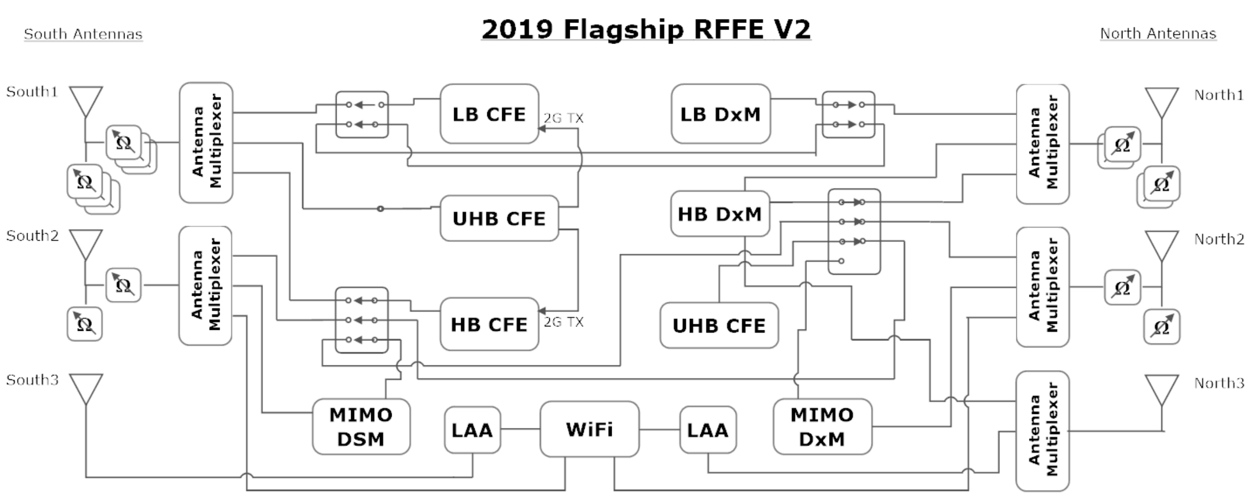


Figure 10: A second possible configuration for an upcoming 5G Apple iPhone

Source: Mobile Experts
(Note that in our diagrams we use the terminology for the "North" end of the smartphone and the "South" end of the smartphone to avoid confusion between "Upper" and "Lower" frequencies.)

For Samsung's Galaxy S11, we anticipate that the architecture will be very similar to S10, but adding a CFE module in the 5G band (e.g. 3.5 GHz). Compared with the Apple configuration, we expect a lot fewer transfer switches due to higher levels of integration in the mid-high band CFE. It's not 100% certain that the 5G NR functionality will be integrated into the mid-high band CFE, but that appears to be the direction that Samsung wants to go. It makes our diagram simpler, but the internal diagram for the "MHB CFE" is very complex.

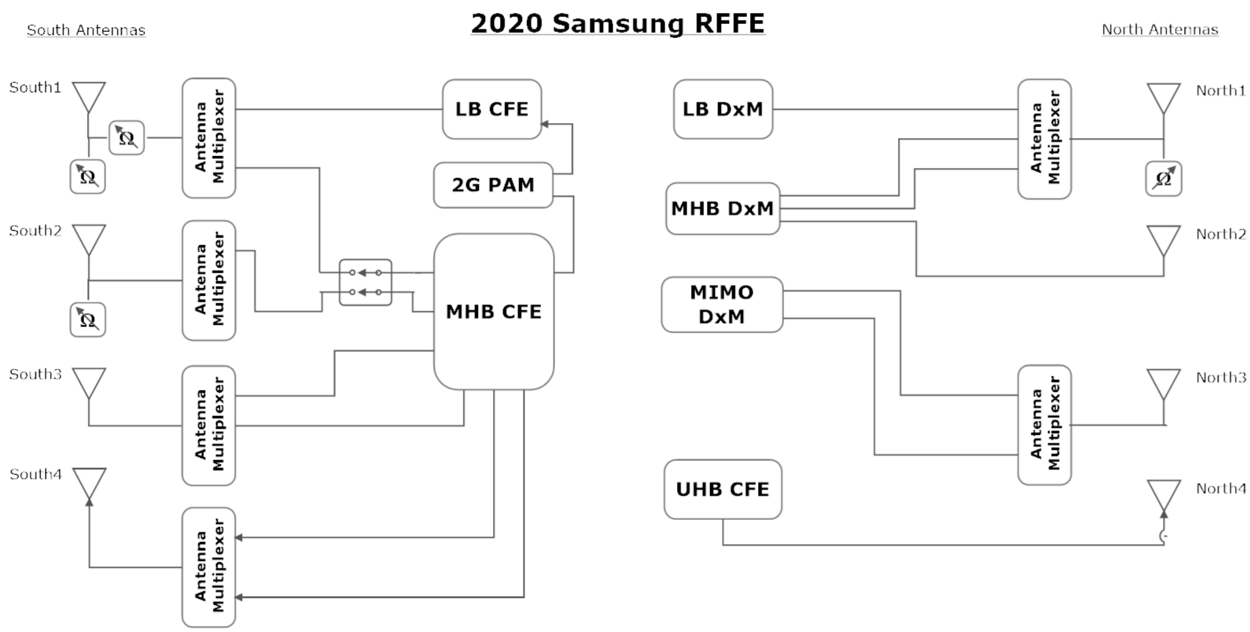


Figure 11: The expected configuration for upcoming Galaxy S11

Source: Mobile Experts

In all of these flagship configurations, the number of antenna-plexer units and transfer switches stands out as one of the most notable aspects. There's a lot of effort and money going into these components for routing signals and keeping bands isolated.

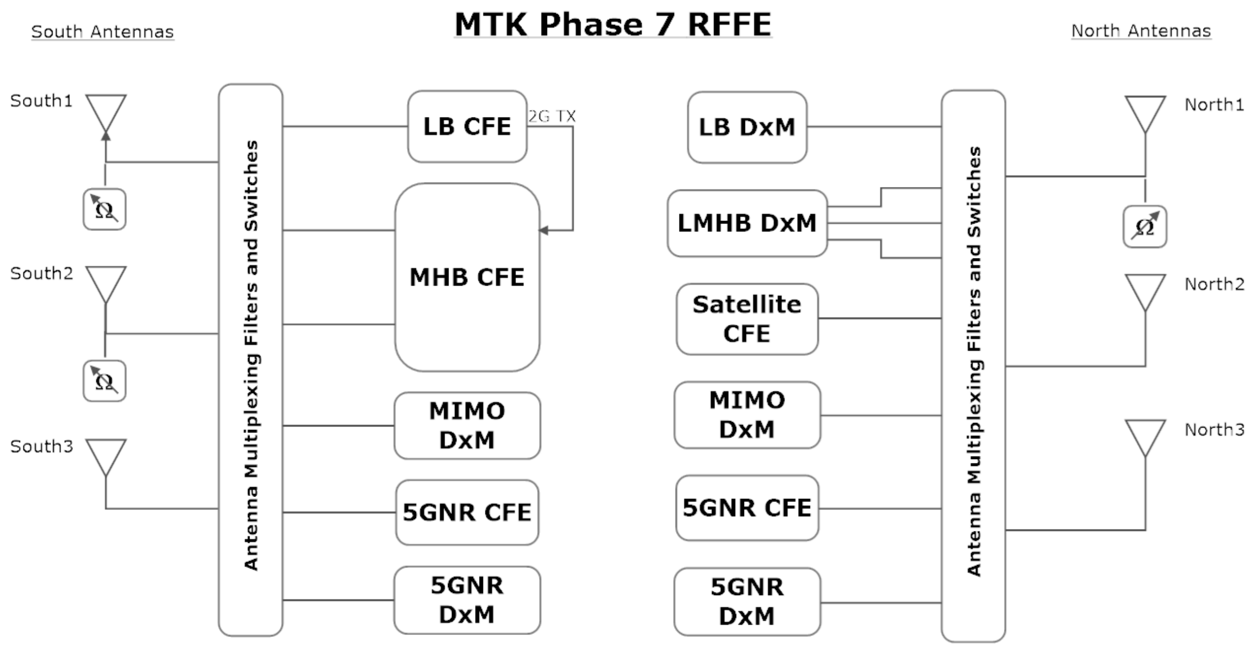


Figure 12: The expected configuration for upcoming Mediatek reference architecture

Source: Mobile Experts

In the case of Mediatek-based designs, we see a simpler configuration with 5G stand-alone CFEs on each end of the phone and their existing CFEs for low-band and mid-high band with high levels of competition. The Mediatek designs include aperture tuning but not impedance-match tuning as seen in the Apple and Samsung flagship designs.

5 FRONT END MODULES

It's not possible to build an advanced smartphone with discrete components anymore (without making a huge phone). To cover 20+ frequency bands and 4x4 MIMO would require a huge space if discrete amplifiers, filters, and switches were used. Over the years, the reliance on integrated Front End Modules (FEMs) has grown to more than 60% of the market.

Mobile Experts defines a FEM as a component with at least two RF functions, such as Power Amplifier, Filter, Switch, or Tuning functions in a common package. Two amplifiers in a shared package without switches, or an amplifier and a CMOS controller, are not considered FEMs by the Mobile Experts definition.

We count FEMs in multiple categories in order to track the direction of the market. Our categories include:

- Antenna Switch Modules (ASM, including bandpass filters and switches);
- Transmit Modules (TxM, including a PA and switch);
- Multimode Multiband PAs (MMPA, including the PA and band switches);
- Switched Duplexer Banks (Commonly called FEMiDs, these include duplexers and band switches);
- Diversity Modules (DRX, including filters, duplexers, and sometimes LNAs);
- Complete Front Ends (CFEs, sometimes called PAMiDs, these include all PA, filter, and switch needs for a group of bands on the main antenna path). Note that the new LPAF modules (LNA, PA, Filter, Switch) for TDD ultra-high band RF are also included in the CFE category… PAMiDs have a duplexer, LPAFs have a filter but otherwise they are similar.)

For many years, the game has been to integrate RF functions, packing multiple die into small modules for high performance using a straightforward 50 ohm interface at the module level. The game is starting to change, as new FEMs are emerging along with Envelope Tracking and inter-stage tuning that work very closely with the baseband modem. We believe that this digital/analog co-design will be important in the future, but it doesn't change the way that we track the physical product shipped. We will keep tracking the categories shown above.

Antenna Switch Modules (ASMs)

An ASM includes an antenna switch and multiple filters. The ASM combines these functions primarily for cost reasons (low parts count) and for smaller size than a purely discrete approach. Of course, the ASM architecture does not achieve the size reduction that is possible with higher forms of integration.   The RF performance benefits of ASMs are small, consisting of low loss from small and direct transitions between components.

Antenna Switch modules are slowly phasing out of GSM handsets, as cheap Transmit Modules are available for the low-end GSM feature phone market, and discrete filters are extremely cheap. The more interesting application is in LTE handsets, where the antenna switch is integrated with a few filters.   For TDD, the antenna switch performs the Transmit/Receive switchover.   In both TDD and FDD, the antenna switch selects a band or group of bands.   The use of an ASM for LTE allows the OEM to separate the PA functionality from the commodity filter/switch functions, which can result in low cost and flexibility between suppliers.   This approach may eventually extend to low-end 5G handsets.

Overall, the ASM approach is not ideal for smartphones with more than 10-15 bands because the critical PA/filter integration is prevented, and efficiency/insertion losses become a problem.

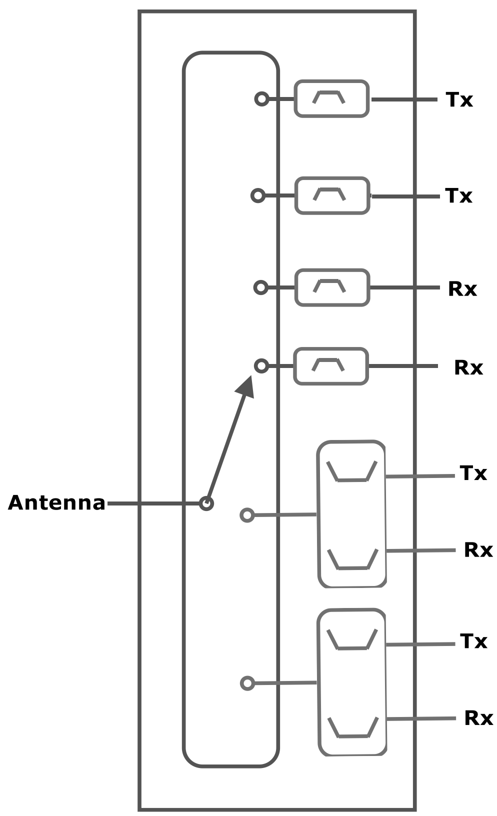


Figure 13:   Block Diagram for an LTE Antenna Switch Modules (incl. GSM, 3G, and LTE)

Source: Mobile Experts

Qorvo, Murata, and Skyworks lead the ASM business with their low cost SAW filters and switches. Not much is changing in this market area, as very little R&D investment takes place at the component level or the handset level for this market tier.

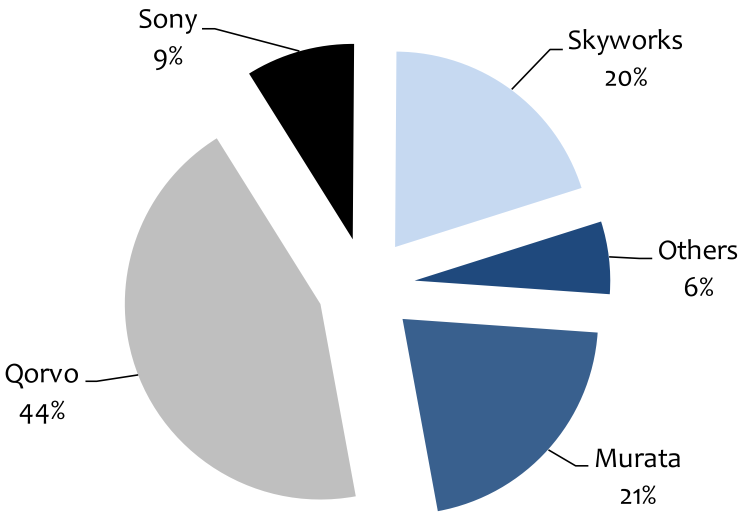


Chart 24: 2018 Market Shares, Antenna Switch Modules (ASMs)

Source: Mobile Experts

Tx Modules

Transmit modules are widely available now from low-cost Chinese suppliers driving very low prices for this simple combination of PA and switch functions.

Note that, unlike PAD integration, this module does not provide major performance benefits (the switches and PA can work better due to fewer transitions and closer proximity, but the boost in PA efficiency is much smaller than for PADs).

Tx Modules can have two Tx paths and either two or four Rx paths (Dual-dual and Dual-Quad configurations). More than 80% of TxMs follow the dual-dual configuration, with the 900/1800 MHz band combination or the 850/1900 MHz band combination. Handsets with quad-band GSM/EDGE performance tend to utilize more discrete devices for the complete solution.

WCDMA Tx Modules consist of a PA with an output switch function integrated, but no duplexer (the fully integrated unit with PA, switch, and duplexer would be considered a Complete Front End).

TD-LTE Tx Modules include the T/R switch and the PA. LTE-FDD Tx Modules are simple single-band LTE PAs, integrated with a switch for 3G or GSM functionality.

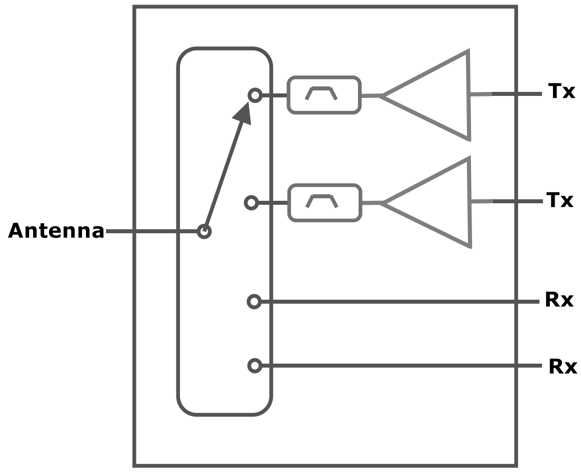


Figure 14: Block Diagram for a GSM Dual-band TxM

Source: Mobile Experts

The GSM Tx Module market is extremely cost sensitive and Chinese suppliers have taken significant share in the low-end market. Airoha supports Mediatek handsets and some others. Vanchip, RDA, and SmarterMicro have each ramped up to tens of millions of units per year. We have conflicting reports about Hunter-sun but we estimate they also have reached a run rate in the tens of millions per year. Skyworks and Qorvo remain with older products here, continuing to sell at low cost.

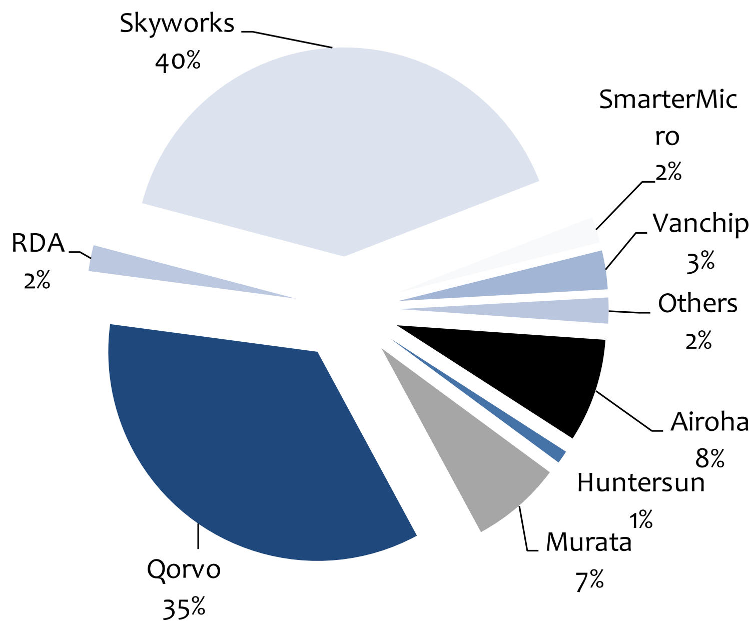


Chart 25: 2018 Market Shares, Transmit Modules (TxMs)

Source: Mobile Experts

Multi-mode, Multi-band (MMMB) Power Amplifiers, or MMPAs

MMPAs change the equation by allowing for operation in multiple bands, and with multiple different waveforms. An MMPA sacrifices efficiency compared to traditional discrete PAs, but can simplify the design for highly complex multi-band handsets. The primary driver for MMPA adoption comes from space savings associated with reducing component count.

Some MMPA modules include GSM PAs (normally implemented as a separate die inside the package due to differences in peak-to-average ratio). Most MMPAs do not include GSM, because many OEMs prefer to buy a cheap GSM Transmit Module separately.

Mobile Experts counts all multi-band, multi-mode PAs in the MMPA segment, whenever more than one generation (2G and 3G, or 3G and 4G) and more than one band run through the same PA component. Note that Mobile Experts does NOT count the MMPA inside a CFE in our MMPA shipments to avoid double-counting.

By definition, MMPAs include switches, to route the amplified signal to the appropriate filter or duplexer prior to transmission at the antenna.

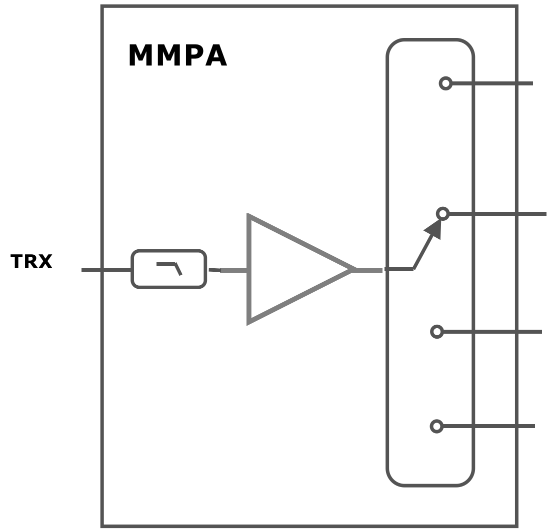


Figure 15: Block Diagram for a Multiband Multimode Power Amplifier (MMPA)

Source: Mobile Experts

The MMPA market is fractured, now that Chinese suppliers have acceptable performance for low-end smartphone applications. RDA focuses their R&D activity in this area, and companies such as Huntersun (Beijing Hantianxia), Airoha (owned by Mediatek) and Vanchip all focus on this segment as their growth platform. The high performance tier is competitive between Skyworks, Broadcom, Murata, and Qorvo.

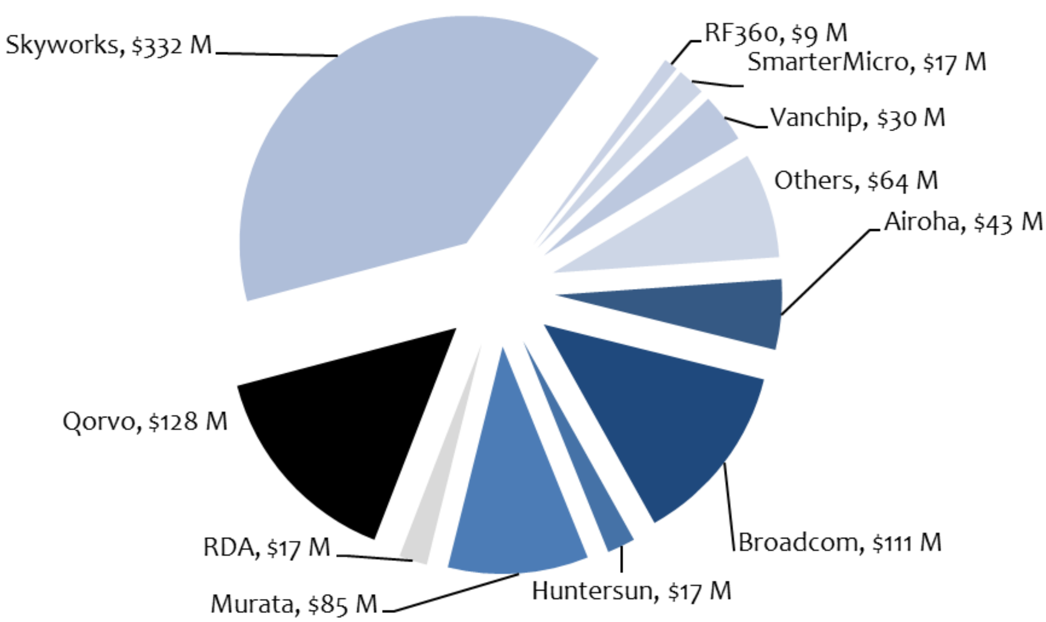


Chart 26: 2018 Market Shares, MMPA

Source: Mobile Experts

Switched Duplexer Banks (aka FEMiDs)

The Switched Duplexer Bank (SDB) is the counterpart of the Multiband Multimode PA for mid-tier devices with about 5-10 frequency bands, as these components allow a common amplifier to match up with a selection of duplexers as needed. The number of bands supported can range from 4-5 in simpler units to 10 or more bands (note that with duplexers this means 10 uplink bands and 10 downlink bands, or a total of 20 paths)

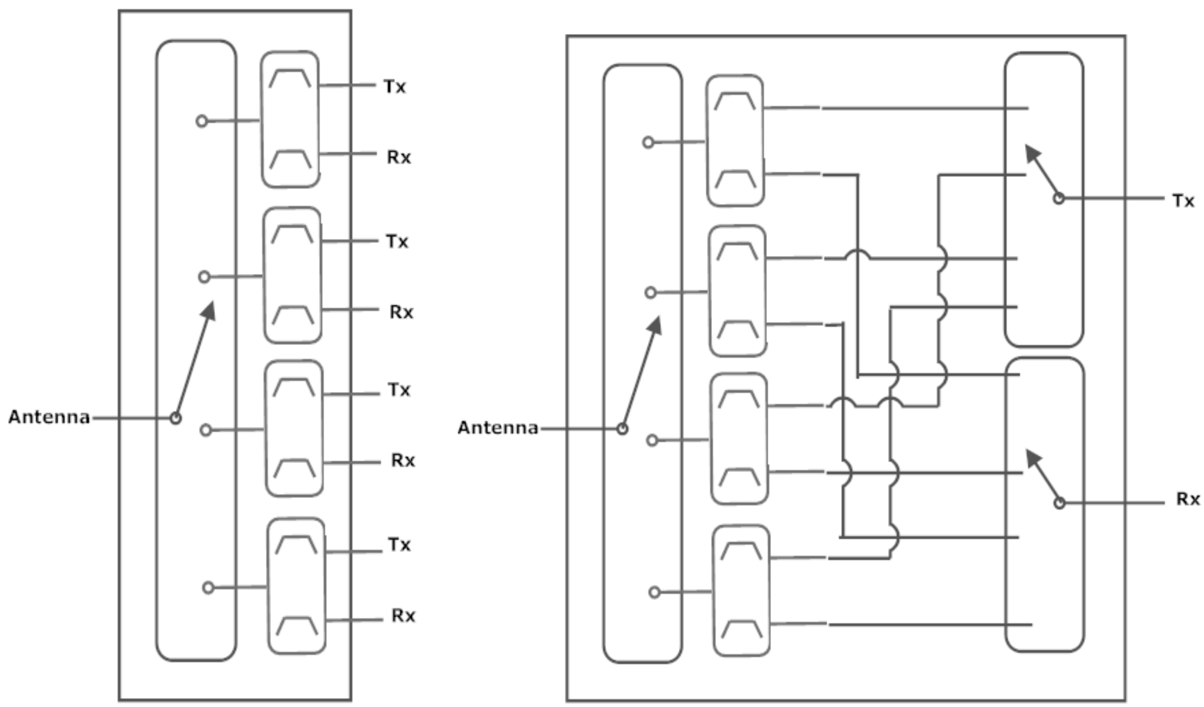


Figure 16: Block Diagram for a Switched Duplexer Bank (two variations)

Source: Mobile Experts

A Switched Duplexer Bank might include only the antenna-side band switch or it might include the PA-side switch as well. Modules with GSM filters are also included in this category when multiple duplexers are involved. Filter-only modules (without any switches) are not included in this category.

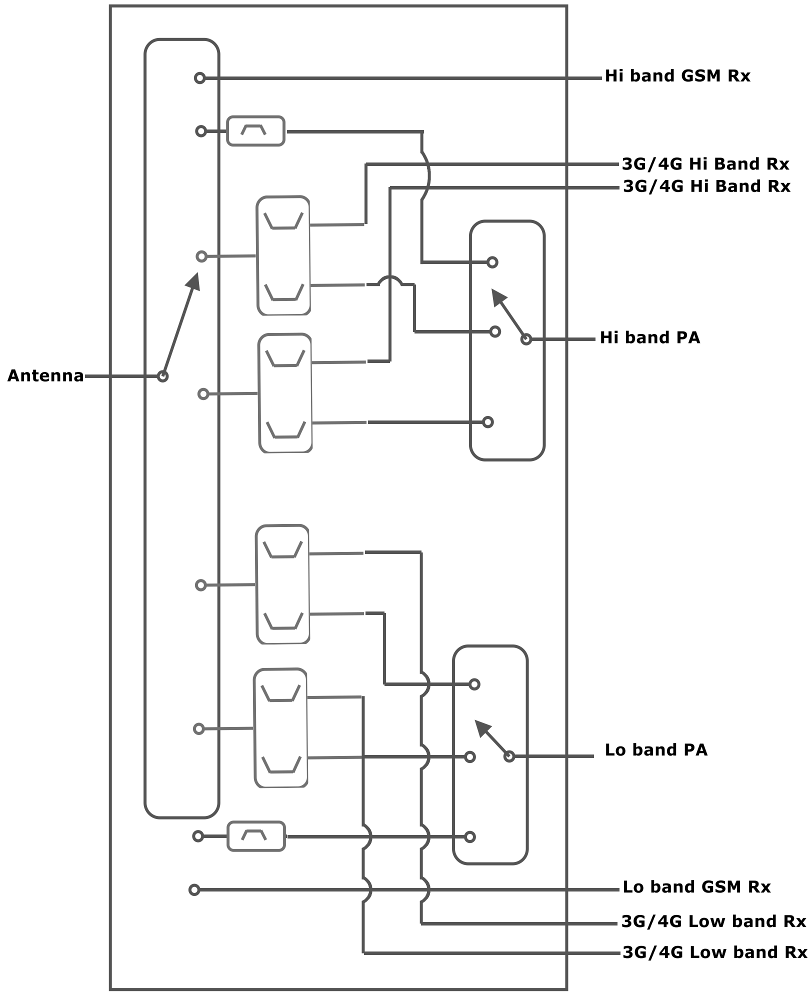


Figure 17: Switched Duplexer Bank variation with GSM filters

Source: Mobile Experts

Filter cost is the main driver for success in SDBs, so this is a game of execution and low cost. Murata and Qualcomm/RF360 both participate heavily in this area and have the dense packaging technology to succeed with complex multi-filter modules.

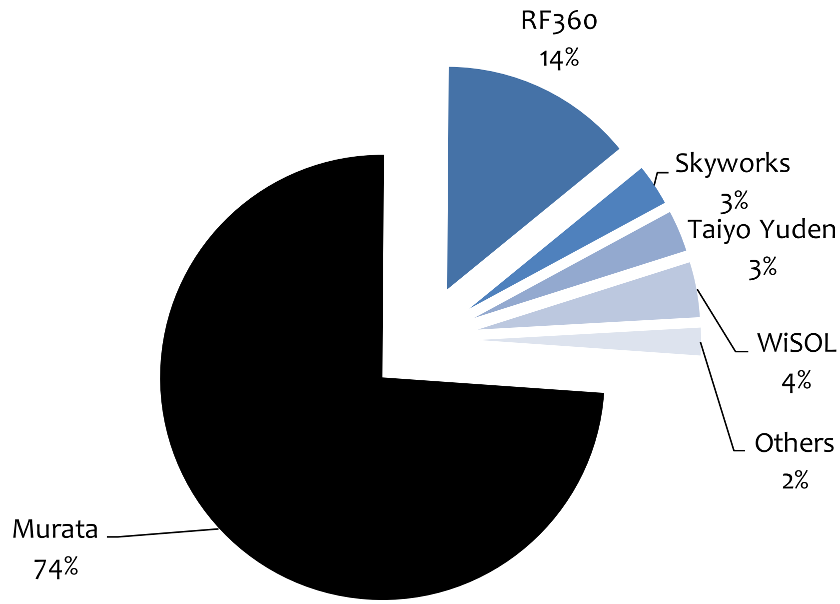


Chart 27: 2018 Market Shares, Switched Duplexer Banks

Source: Mobile Experts

Diversity Modules

The Diversity Module market has become one of the fastest-growing segments, as 4x4 MIMO is adopted in large numbers of bands. The Diversity Module provides the receive-only filtering for MIMO antennas, essentially replacing the filter capability of a CFE solution for antennas that handle the downlink only. LNAs are also integrated in many of these modules… as the number of bands grows, the insertion loss of the filter module gets higher and the receiver needs an LNA in the RFFE to compensate.

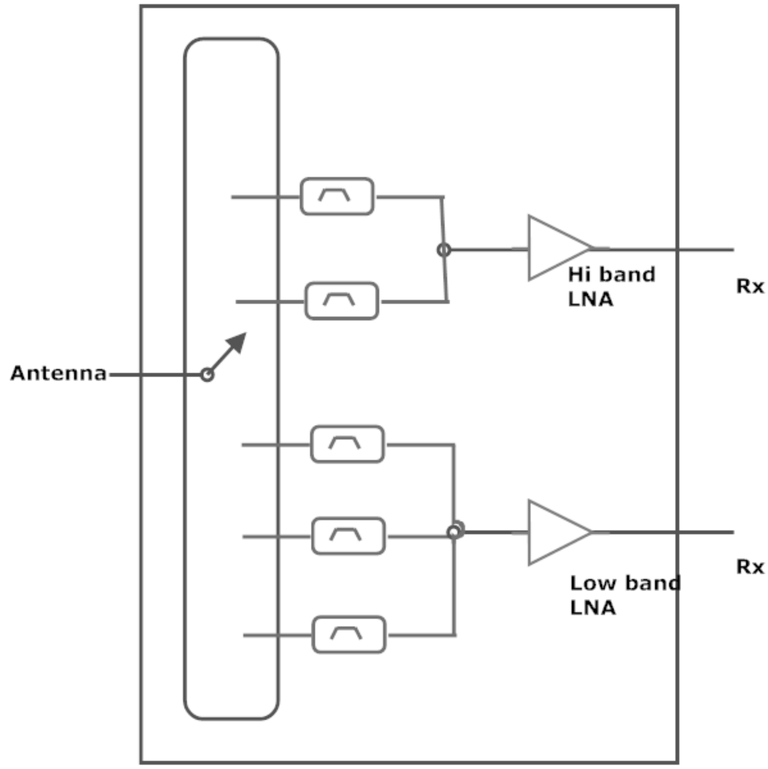


Figure 18: Receive Diversity Module Block Diagram

Source: Mobile Experts

Murata and Skyworks dominate the DRx market with tight packaging and low cost. Qorvo, RF360, Taiyo Yuden, and WISOL also participate in this market as at least 16 different handset vendors now offer MIMO in LTE handsets.

Diversity modules with up to 16 bands are used in premium handsets….with as many as 5-6 LNAs in some modules due to the wide bands shared on common antennas. Performance requirements are often not the primary driver here: Small size, yield, and low cost manufacturing excellence are the key factors for major smartphone vendors.

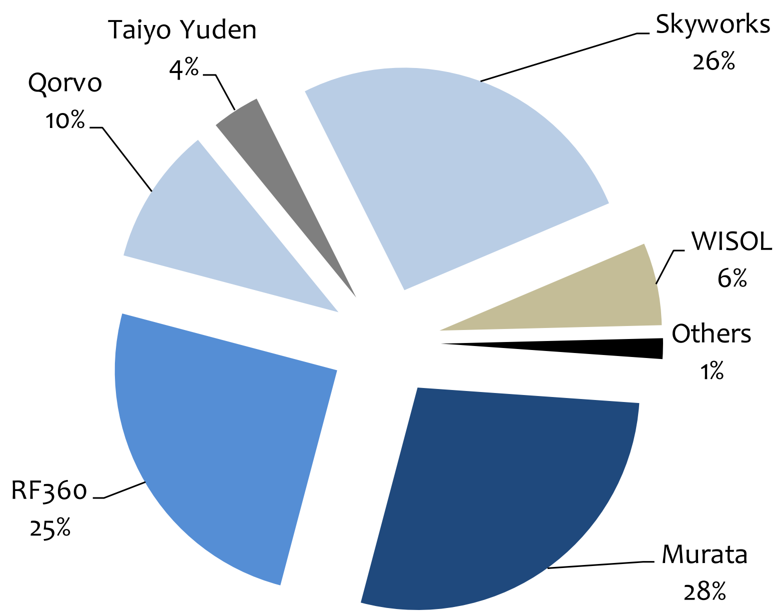


Chart 28: Market Shares, Diversity Modules (DRx), 2018

Source: Mobile Experts

PA/Duplexers (PADs)

PADs were introduced in the days of 3-5 bands in a handset, to take advantage of the inherent performance benefits of co-designing amplifier and duplexer together. The market has moved upward to higher levels of integration now, with only a few customers using PADs as a 'semi-discrete' way to handle odd FDD bands.

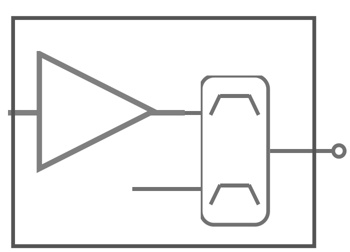


Figure 19: Block Diagram for a PA/Duplexer (PAD)

Source: Mobile Experts

Qorvo, Skyworks, Murata, and Broadcom are natural contenders in the PAD market, with both filter and PA capability in each company. However, none of these companies put much focus into the PAD market anymore because the architecture has moved on to Complete Front Ends. So today's PAD market has seen longer product life cycles and little investment.

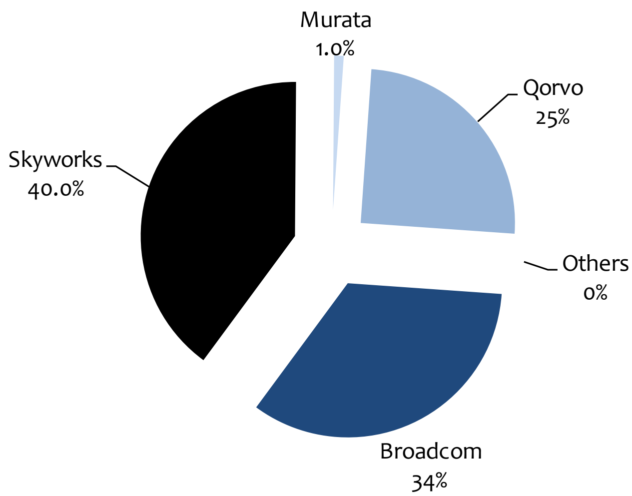


Chart 29: Market Shares, PADs, 2018

Source: Mobile Experts

Complete Front Ends (CFEs, including PAMiD, LPAMiD, and LPAF)

Complete Front Ends (CFEs) have taken the prime position in the smartphone market, because CFEs represent the best way to jam a huge number of filters and PA functionality into a very small size and power budget. This architecture has fundamental advantages over the MMPA/Switched Duplexer Bank approach, because the close PA/filter integration provides better battery performance. The density of packaging in this type of module also results in the smallest possible form factor.

Our definition of a Complete Front End is a module that contains the filter, PA, and associated switch functions for a group of frequency bands.

Most mid-tier and high-tier smartphones now use CFEs, with two or three modules to cover low band, mid band, high band, and ultra-high band. We expect almost every phone with more than 15 bands to move toward this architecture, while less complex handsets can use the TxM/MMPA approach (such as Mediatek Phase 2/Phase 3).

The CFE design has become sophisticated, with quadplexers or hexaplexers built in, along with LNAs to optimize receiver sensitivity. The level of electromagnetic modeling and design / packaging expertise needed has become so high that smaller PA vendors (such as RDA, Airoha, Vanchip) may not be able to compete.

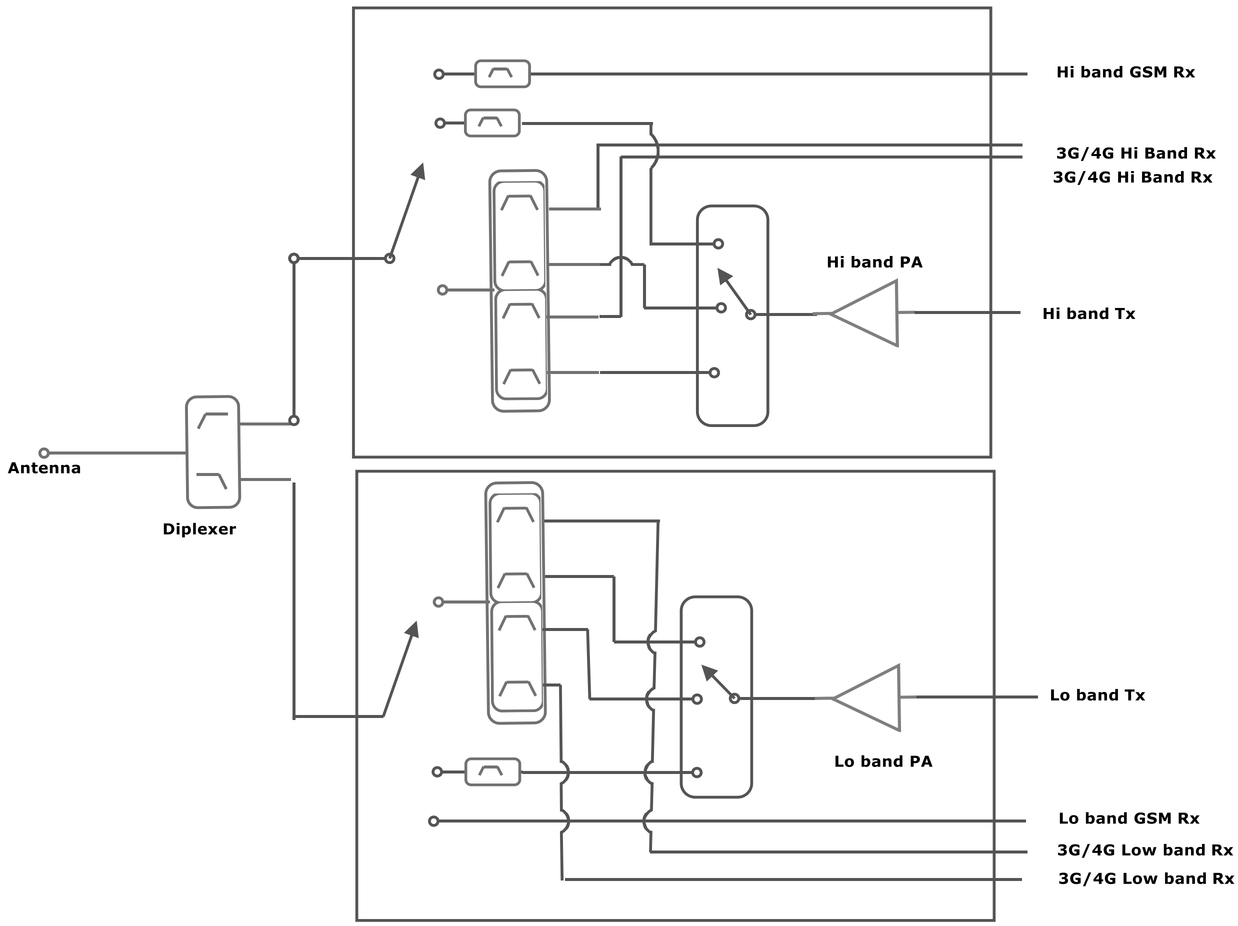


Figure 20: Block Diagram for CFE implementation incorporating multiplexers for each band group

Source: Mobile Experts

The frequency groupings for CFEs are determined by the OEM's strategy for managing suppliers and complexity. Generally, the low bands are grouped together, from 600 to 950 MHz. Mid and high bands are grouped together (1700 to 2500 MHz) and ultra-high bands are emerging at 3.5 to 5 GHz. It's simply not practical to fit 5 different CFEs into a smartphone, so combining them is the best strategy to save on space.

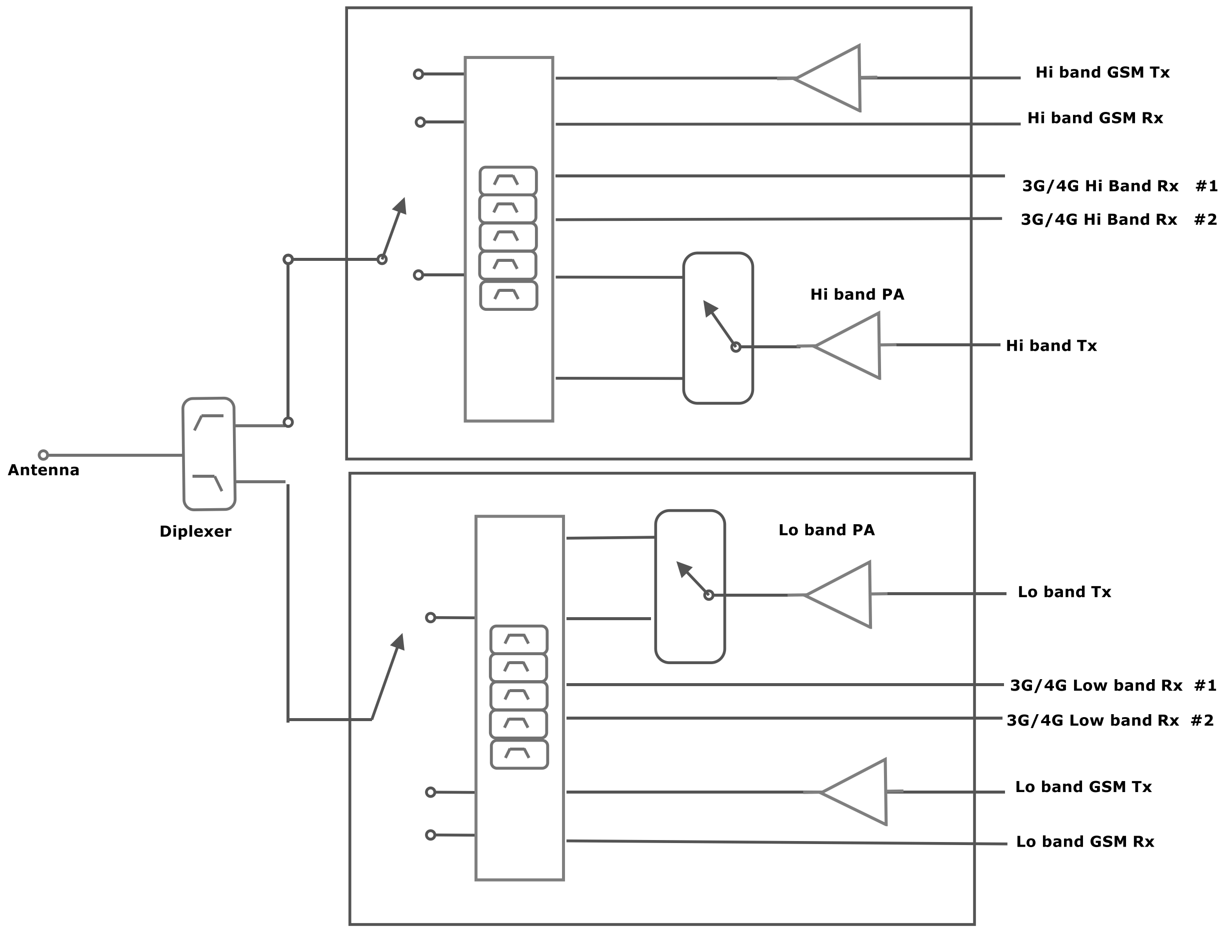


Figure 21: Block Diagram for a simplified CA Handset with multiplexed FEMs

Source: Mobile Experts

The billion-dollar question for CFEs: Will Uplink MIMO become a standard feature? If so, then the number of CFEs will grow much more quickly, driving significant content growth in smartphones. In platforms with very high volume, we expect that not all bands need to be duplicated (e.g. FDD bands don't need uplink MIMO), so the bigger customers would opt for an optimized second CFE for TDD bands only.

Broadcom held a dominant position in mid-high band CFEs, but recently Qorvo and Qualcomm have started to encroach on their territory, and Broadcom's share has dropped.

Skyworks has been very successful in the low-band segment, but they are facing low-cost competition from Qorvo and Qualcomm, as well as MuRata in som cases.

Qualcomm/RF360 is now competing strongly with their unique combination of RF modules with Envelope Tracking and coordination with a Qualcomm modem. The technical synergy didn't matter so much in 2018 (Qualcomm's growth in 2018 was mostly a result of bundling with smaller customers for a strong RF attach rate), but in the future we expect the technical advantages of modem/RF co-design to help Qualcomm's share in CFEs. In particular, watch for a step up with 5G phone introductions in late 2019.

We've seen some interesting prototypes from SmarterMicro, RDA, and Airoha, but no significant design wins so far. We believe that the technical challenges will make this segment difficult for the smaller PA shops to penetrate during 2019.

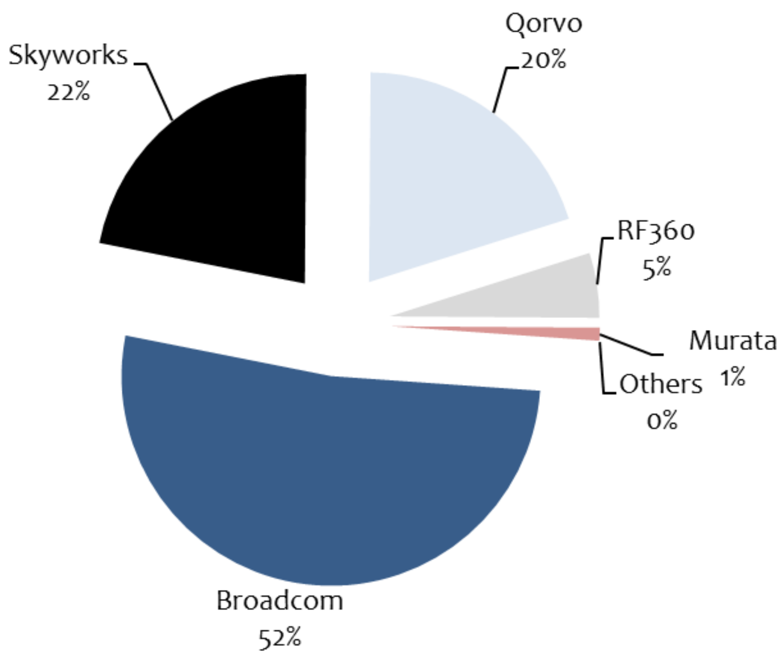


Chart 30: Market Shares, CFEs, 2018

Source: Mobile Experts

6 FILTERS, DUPLEXERS, MULTIPLEXERS, ANTENNAPLEXERS

The basic physics of RF filters dictates that we use a separate die for every unique band. That means that adding new bands and MIMO modes keeps increasing the number of die…we now have more than 75 filter die in some handsets!

At a strategic level, FBAR and BAW technologies held a decisive advantage for many years, but that advantage is now changing as we move from FDD bands (narrow slices, close together) to TDD bands (wide slices, with coexistence issues). BAW and specifically FBAR are useful for the new applications but may not be as critical as in the race for hexaplexers and other complex FDD designs.

Alternative technologies such as single crystal BAW and thin-film SAW are now getting more mature and should make an impact on the market. The high Q and K^2_{eff} achieved in new technologies are useful in the wideband, squared-off filter applications, and may also be useful in tunable filter concepts.

SAW, TC-SAW, BAW, and FBAR Technologies

Surface Acoustic Wave (SAW) technology uses a piezoelectric crystal with an acoustic wave to achieve high quality filtering at an extremely low cost. SAW filters represent more than half of the market today, because the simple processing of a SAW device is the best way to address very high volume filter requirements that don't have extreme performance needs.

Bulk Acoustic Wave technology uses a different acoustic mode in the filter, and a variation known as Film Bulk Acoustic Resonator (FBAR) filters is the best example of high resonator quality factors, for steep cutoff in the filter design. BAW and FBAR devices are generally sold at higher prices than SAW devices to account for the premium performance. Generally, BAW devices can operate with low loss and steep cutoff at higher resonator frequencies than SAW filters.

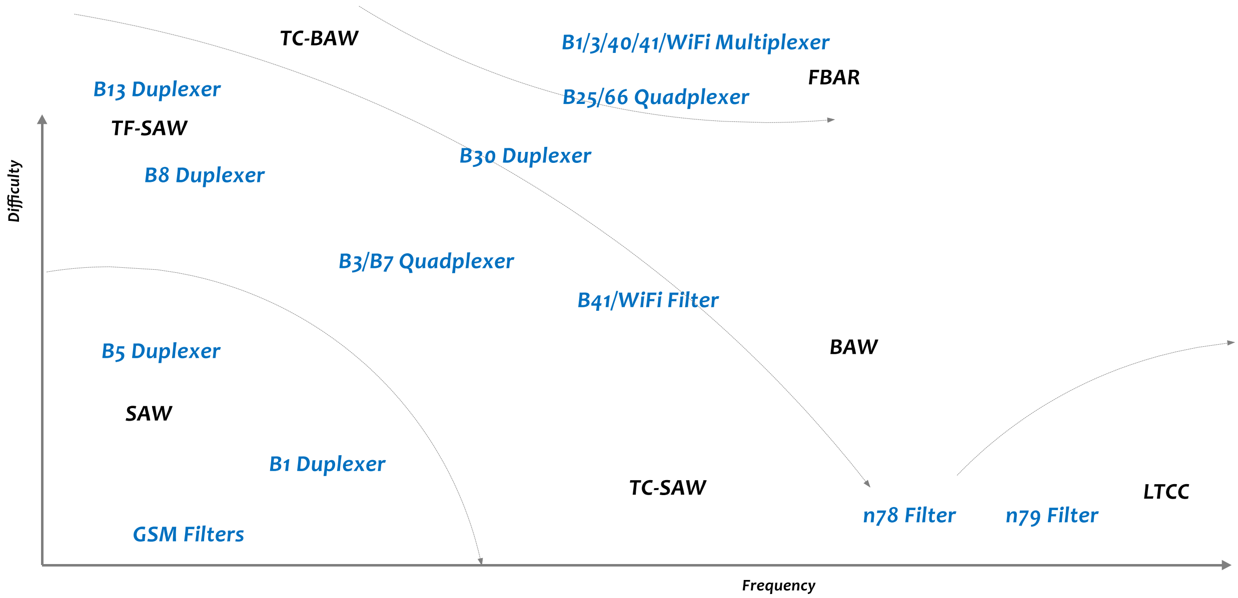


Figure 22: Sweet Spots for SAW, TC-SAW, BAW, FBAR, LTCC, and TF-SAW

Source: Mobile Experts

Thin-Film SAW (TF-SAW or IHP)

Multiple companies are now developing SAW filters using thin-film deposition of piezoelectric material on CMOS wafers or GaAs wafers. There are numerous challenges associated with the wafer surface, temperature expansion, and other fundamental properties of the semiconductor wafer. But the potential benefits of integration could be worth the challenge.

One intriguing possibility is the coexistence of filters/resonators and active elements on the same wafer. What can change if we eliminate the transitions between different die? Over the past twenty years, shorter distances and simpler transitions between devices has always resulted in a step-function improvement in performance.

Products are a little slow in coming to market, but MuRata has demonstrated a Band 25/66/30 hexaplexer, illustrating the high Q values for their version of the technology. Other information that we can share publicly is sparse at this point.

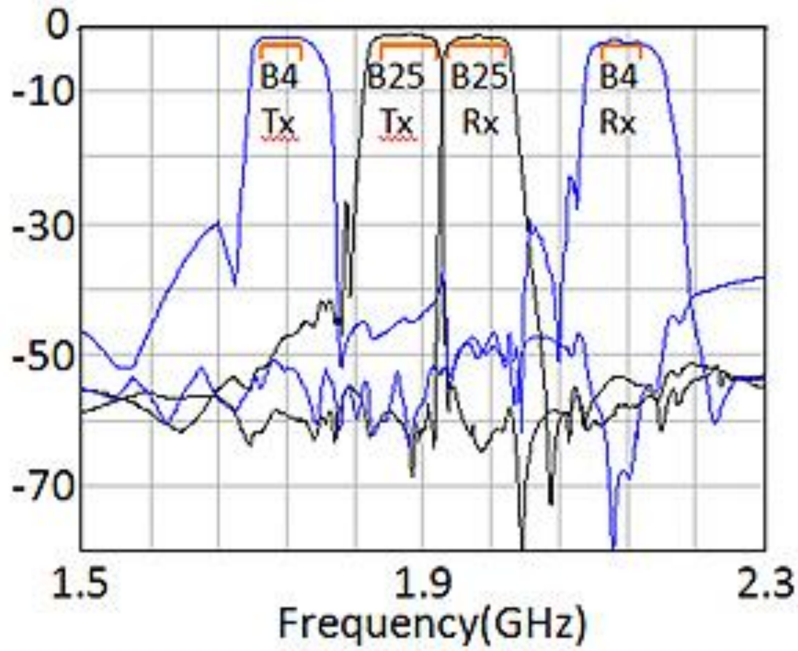


Figure 23: 2018 Quadplexer performance of IHP (Thin-film SAW) technology

Source: Murata

Extractors" or "Antenna-plexers"

Today's smartphones have as many as 11 antennas to deal with 4x4 MIMO in the high bands, 2x2 MIMO in the low bands, plus Wi-Fi, GPS, NFC, Bluetooth, and other radio signals. To consolidate, the flagship platforms now use "extractor" or "Antenna-plexer" " filter modules which allows a shared antenna to be multiplexed for these very different purposes. A typical Extractor allows 2.4 GHz and 5 GHz Wi-Fi, GPS, Hi-band LTE, and Lo-band LTE to share a single wideband antenna.

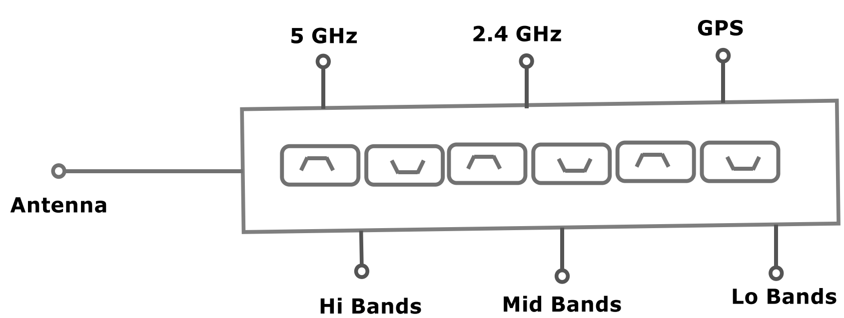


Figure 24: Functional Diagram for a "Extractor" or "Antenna-plexer"

Source: Mobile Experts

This approach is catching on, and multiple factors will drive growth in this area:

- 4x4 LTE MIMO drives a need for three diversity antennas to separate mid and high bands for diversity modules;
- 4x4 MIMO for LAA and Wi-Fi drives a need to separate licensed and unlicensed signals;
- GPS may be moving to a multi-band receiver approach soon, with L1 and L5 frequencies, and even adding the L2 frequency at some point in the future.
- Bluetooth is also in the mix. We haven't seen Bluetooth added to these yet but we're watching for that possibility.

Disruptive Filter Technology

The RF filter market is so attractive that new ideas come up constantly—there's no shortage of people that want to disrupt a $8B market. However, some ideas have dropped off the map, and others have risen up to look more promising:

- Resonant Wireless has reached production volumes for their licensing of SAW-based filter designs with high performance, and now has developed an advantage in design of wideband filters (600+ MHz bandwidth) with sharp skirts.
- Abtum has been working on enhancement of filters with advanced broadband cancellation. They have a method for enhancing rejection by 20-30 dB, essentially enhancing the Q of SAW filters.
- Akoustis has gradually made their way from basic materials to complete filter products and have now introduced some WI-FI coexistence filters as well as LTE filters to production volume.
- In addition to the start-up companies, RF360 has been working on a technology which combines intelligence in the modem with aggressive tuning in the RFFE. The idea is to focus on the actual RF signal transmitted, not the entire band. In changing the rules of the game, the RF360 filter concept could improve insertion loss and rejection at the same time. It's not clear yet whether this technique would apply when the channel is assigned at the band edge.

Filter Market Shares

As filter growth becomes more dependent on integration into modules and less driven by specific filter technologies, we see some 'evening' of the playing field with TC-SAW solutions competing with BAW solutions and other combinations. The high performance "antennaplexers" and hexaplexers still tend toward using BAW/FBAR techniques for now, but new techniques are getting closer.

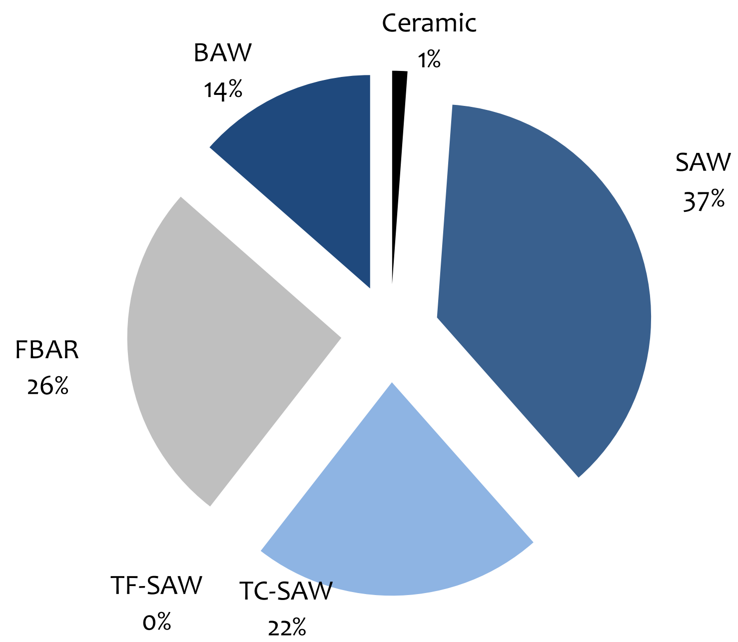


Chart 31: Percentage of Filter Revenue, SAW,TC-SAW, BAW, FBAR, TF-SAW 2018

Source: Mobile Experts

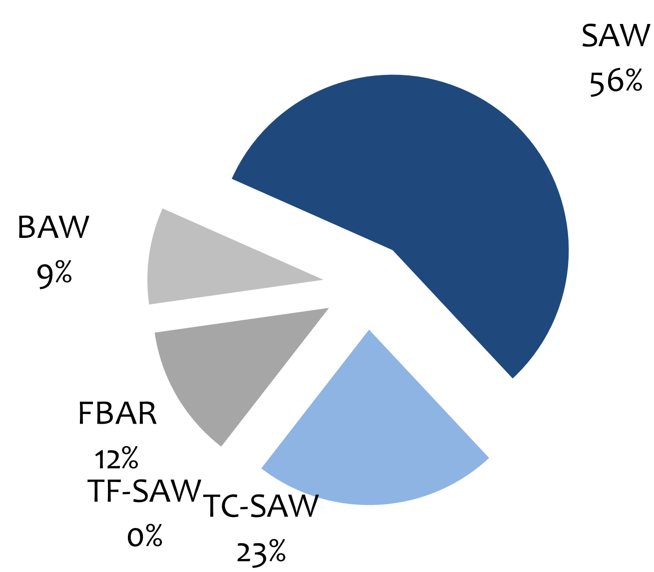


Chart 32: Filter Die Shipments, SAW,TC-SAW, BAW, FBAR, Ceramic and TF-SAW, 2018

Source: Mobile Experts

The filter market is controlled by five companies that combine for 90% market share: Broadcom, Murata, Skyworks/Panasonic, Qorvo, and Qualcomm/RF360. Challenging specifications are still driving performance, so FBAR, BAW and TC-SAW filters are taking an increasing share of the overall total.

Second-tier filter vendors such as WISOL, Taiyo Yuden, and Tai-SAW are still providing a solid share of the market as well, although their participation is more limited to lower performance and discrete filter applications. We're not tracking Resonant or Akoustis products yet, but we expect to see enough volume in the coming years to start tracking their share.

The market shares shown reflect the estimated RF content in several types of modules. Because the majority of the filter market is now intimately tied to PADs, filter banks and duplexer banks, as well as various other switched filter modules, accounting for filter "revenue" is somewhat arbitrary. Mobile Experts has estimated the value of filter content so that we can illustrate the relative share of each company. Our assumptions are listed in the spreadsheet that accompanies this report.

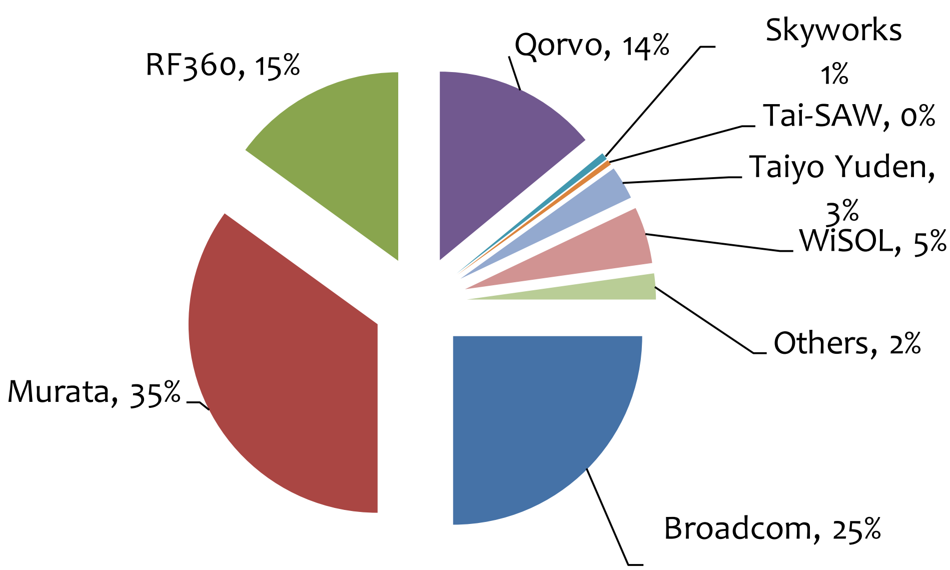


Chart 33: 2018 Market Shares, Overall Filter Content in Mobile RF Front Ends

Source: Mobile Experts

7 SWITCHES

Some premium smartphones can have over 100 switches in the RF front end, but nobody notices because the switches are mostly integrated with other functions, in CFEs, switched duplexers, diversity modules and other FEMs. We distinguish between a few basic types:

- Band switches are typically single-pole, multi-throw devices that govern selection between bands in many handsets. For 2G and 3G handsets, about 1/3 of terminals still use discrete band switches in this way… Carrier Agg is not an issue and this can be a simple and flexible way to stitch together the discrete RFFE.
- Transmit/receive switches govern the connection of PA or receive RF path in TDD systems. High linearity is required for this function.
- Transfer switches are a more complex combination of elements to cross-connect different antennas. This function is becoming increasingly important as 4x4 MIMO becomes standard in the high bands, making multiple transfer switches necessary in premium phones.
- (Note that we cover a fourth category, tuners, in a separate section. In many cases the 'tuner' is, in fact, a simple RF switch that connects to multiple capacitor options.)

Overall, the discrete market for RF switches weighs in at $700M per year (excluding tuners).

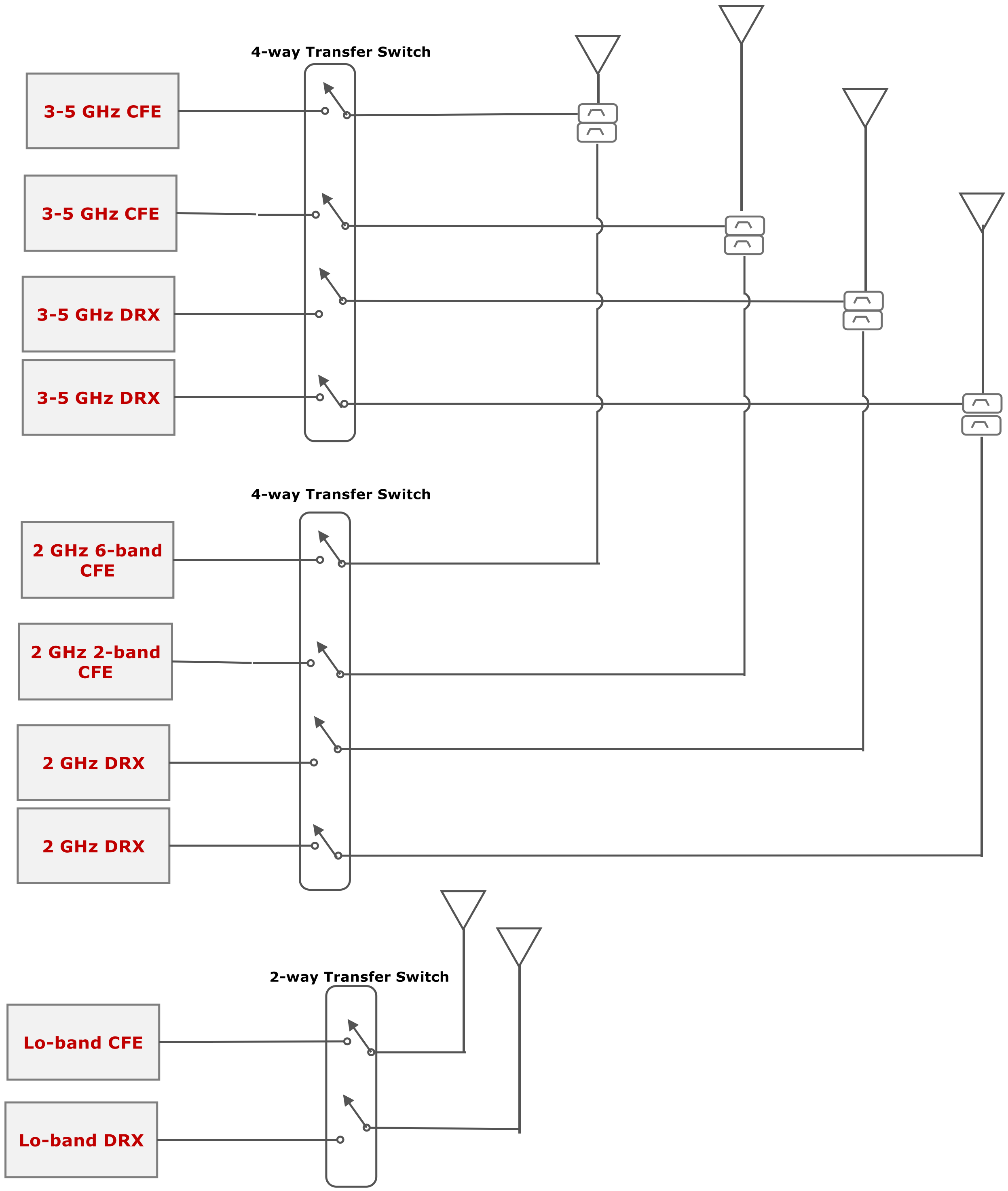


Figure 25: Block diagram for Transfer Switches in a 5G handset with 4x4 MIMO and UL MIMO

Source: Mobile Experts

When it comes to market share for switches, many participants make the scoreboard, because band switches, antenna switches, and transfer switches can have very different performance characteristics. Several process technology variations can now achieve the high linearity requirements, so any company can find a fab to work with.

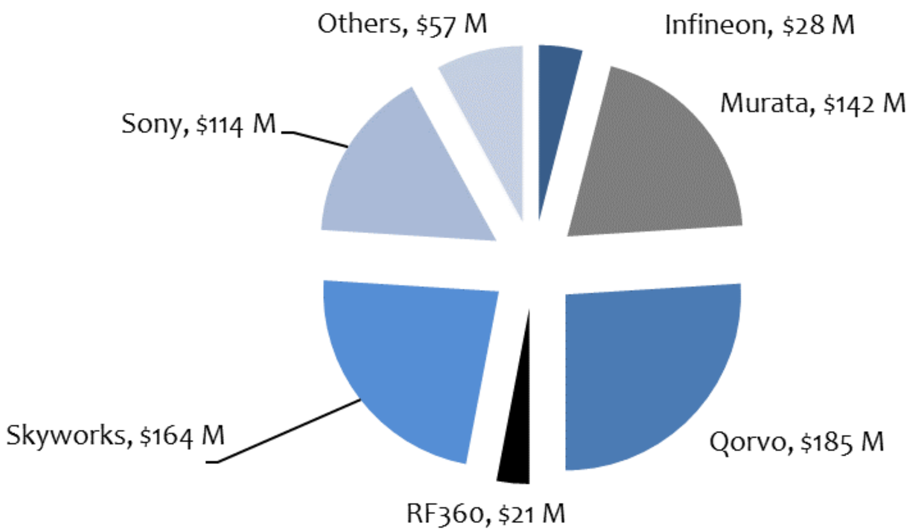


Chart 34: Market Shares, Discrete Switches, 2018

Source: Mobile Experts

8 LNAs

Large numbers of bands attached to an antenna means that a filter bank will have significant insertion loss. With 4-5 dB of loss, the receiver's noise figure suffers from poor sensitivity and needs some help. For this reason, LNAs are coming back into the market, both in discrete form and as a part of diversity modules.

Semiconductor Process Technology

SiGe, GaAs, Silicon CMOS are all possible for LNAs in the smartphone application. CMOS is popular here because of low cost. If the SOI/CMOS process can handle the linearity requirement, then most module vendors will use it to keep costs as low as possible. SiGe is used by discrete LNA vendors such as Infineon and NXP, providing better noise figure performance.

In our opinion, performance is not as important in the LNA market as in power amplifiers or filters. As LNAs are integrated into the FEMs, the choice of technology is left to the module supplier, and the actual performance of the LNA is lost in the overall performance of the module. One or two tenths of a dB lower noise figure is not visible at the module level….so the overall module is designed around the key PA/filter functions and then the most convenient and 'integratable' LNA is chosen.

Chart 35: LNA Technology Shares, CMOS vs GaAs vs SiGe, 2018

Source: Mobile Experts

Integration with FEMs

LNAs are routinely integrated with Diversity Modules and Complete Front Ends (PAMiDs), with each LNA covering each band group (such as low-band, mid-band, high-band, etc). As the LNA has become a normal part of the modules, many larger module suppliers are migrating toward RF CMOS for lowest cost and potential integration with switches and the MIPI controller.

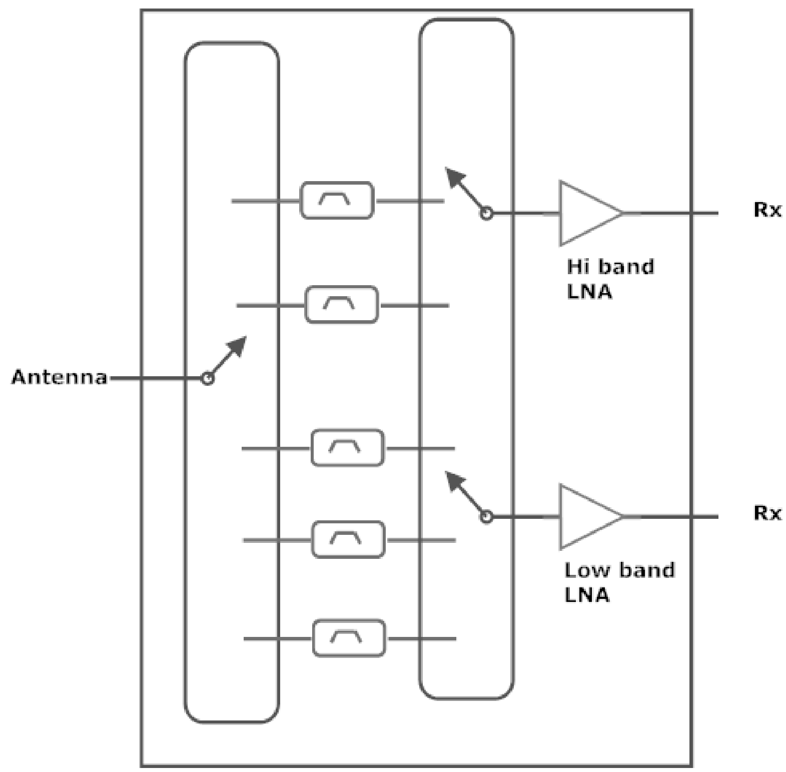


Figure 26: Block Diagram for a Diversity Module with integrated LNAs

Source: Mobile Experts

For high-end smartphones, we expect LNAs to be integrated with both diversity modules and CFE modules. The high band count drives the primary need for LNAs. Handsets with fewer bands (that don't use diversity modules and CFEs) use discrete devices, but don't need LNAs as much. As a result, we're projecting that over time, about three quarters of the LNA market will be integrated into FEMs.

Integration with CFEs

Complete Front Ends incur significant loss in the receiver chain, as the signal must pass through a complex filter structure to reach the receiver. The losses can stack up to 5 dB or even more in these complex handsets with Carrier Aggregation…so that's 5 dB higher noise figure at the front of the receiver! CFEs now include LNAs as a part of the overall design, and suppliers are rapidly adopting this approach to help improve performance. Including an LNA can improve the noise figure performance of the CFE, allowing higher loss in the filters or different placement of filters to relieve one of the constraints on the overall CFE design.

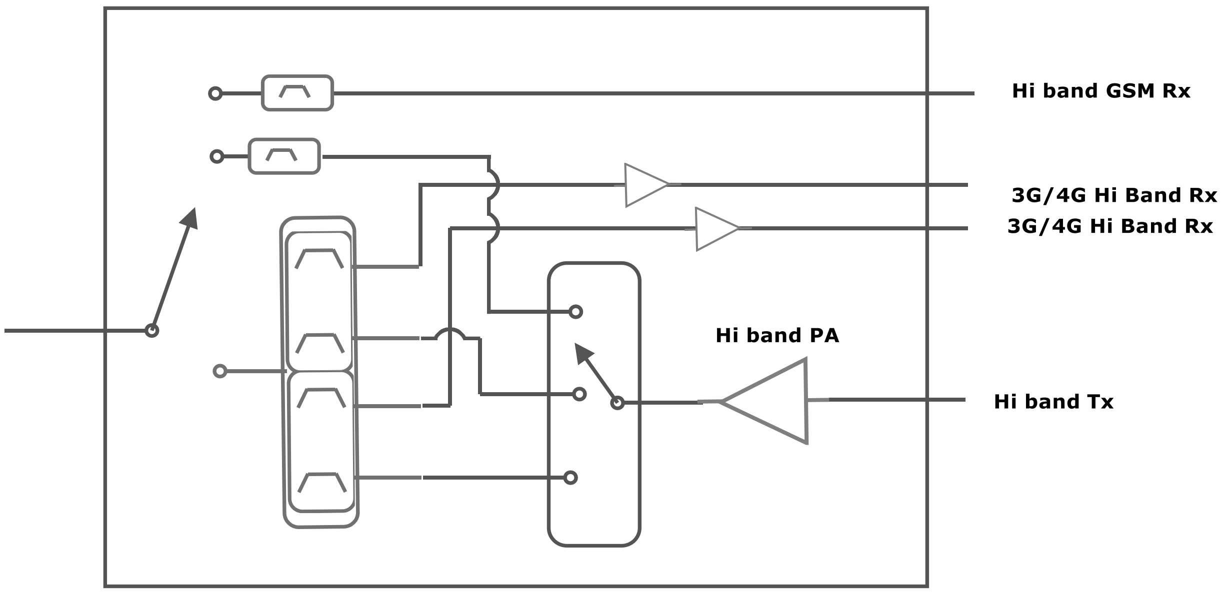


Figure 27: Block Diagram for a Complete Front End with integrated LNAs (LPAMiD)

Source: Mobile Experts

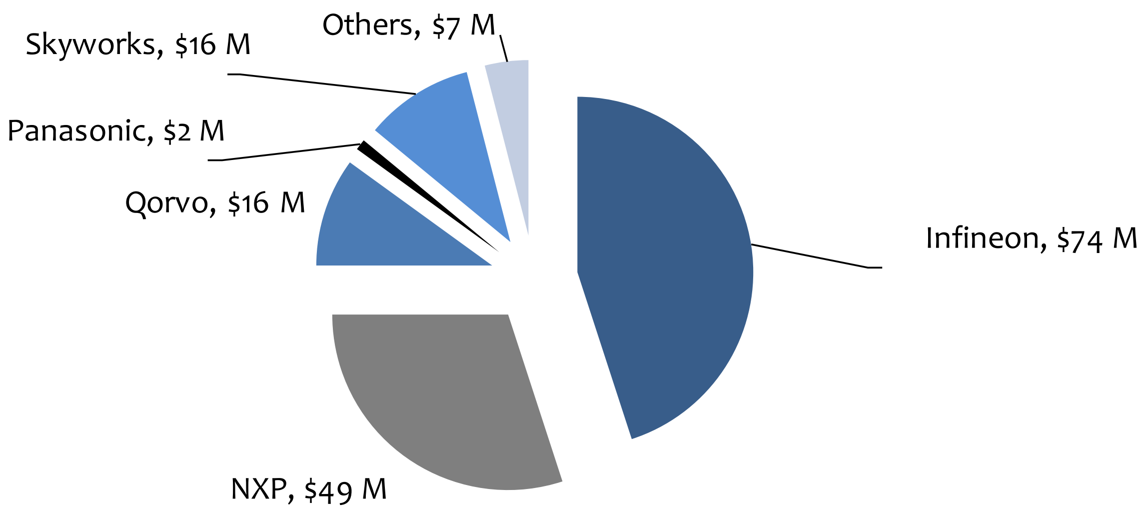


Chart 36: Discrete LNA Market Shares, 2018

Source: Mobile Experts

9 TUNING ELEMENTS

Low-band Antenna tuning has become a standard feature in smartphones. "Tuning elements" can be made up of discrete switches, or switches with built-in capacitors, or even other components such as inductors. For the past few years, these tuning elements have been focused on aperture tuning, to move the frequency of an antenna as needed. New architectures explore the use of inter-stage tuners for amplifiers or filters to optimize performance. We do not include those tuning components in this section because inter-stage tuners are likely to be integrated on the die with the RF function.

We're continuing to track two main use cases for tuners here:

- **Aperture Tuning**: Tuning elements or switches can be used to change the electrical length of the antenna itself, varying the resonant frequency of the antenna structure and improving antenna efficiency.
- **Impedance Tuning**: A network of matching elements can be inserted between the switch/duplexer module and the antenna. This approach adjusts the antenna's impedance match to compensate for head, hand, and other environmental loading factors on the antenna.

Aperture Tuning Approaches

The baseline for aperture tuning is a simple SOI switch with multiple capacitors for various desired frequency responses in the antenna. That's a simple and easy way to move the frequency around. However, the simple SOI switch is starting to be replaced by MEMS devices, because the lower loss of MEMS results in better performance at the phone level. In addition, MEMS offers higher voltage handling, which allows the component to sit in more advantageous locations on the antenna itself, for greater tuning range.

The increasing use of tuners has brought new use cases out into the open. For example, the aperture tuner can be useful in re-tuning the antenna when the user plugs in the cord and de-tunes the low band antenna. In addition, the antenna match can be tuned to the channel of interest, not just to the band of interest. The modem knows what channel is used and can fine-tune a DTC to step into precisely the right frequency setting. This can actually reduce the rejection requirements for a filter, but we don't see the OEMs taking advantage of that possibility yet.

The combination of tuning range, lower resistance (R_{on}), and lower C_{off} allow the MEMS devices to adjust for variations in the industrial design. Where different SOI switches might be required to meet the unique needs of an industrial design (some need lower 'off' capacitance, and others need lower 'on' resistance), a single MEMS product has the low loss and low capacitance to be applied to any scenario. For handset OEMs, this is key, because the actual performance of a handset with its antenna is not known until production is ready to start… and a last-minute surprise in TRP/TIS testing will often result in a scramble to find a slightly different SOI switch. This means that MEMS switches have value beyond the simple performance benefits as a component.

Overall, switches for aperture tuning have become extremely common for low-band antennas, and we now have increasing adoption in high bands.

- Simple SOI antenna switches have been the most successful approach so far, simply changing the electrical length of the low-band antenna for the intended use. The most common use is to switch shunt capacitors in at a tap point located on the antenna structure.
- Switches can also be used to switch inductors, where the native frequency of the antenna itself is at a low frequency and the resonant mode must be shifted higher. This is done either with SOI switches or MEMS switches today.
- Digital tuning capacitors can be used to select among many different capacitor states, offering greater resolution and better performance over a large tuning range than the discrete switch-and-capacitor approach. The DTC can be realized with either SOI or MEMS switches.

Is there a conflict between Aperture Tuning and Carrier Aggregation?

In concept, the aperture tuning approach uses a narrowband antenna design, moving the resonant frequency around to suit a single frequency band for operation. However, in cases where Carrier Aggregation uses two or three bands on the same antenna, things get more complicated. It is possible to independently tune multiple resonances on an antenna structure, so with some clever engineering it's possible to use aperture tuning in a complex Carrier Aggregation application.

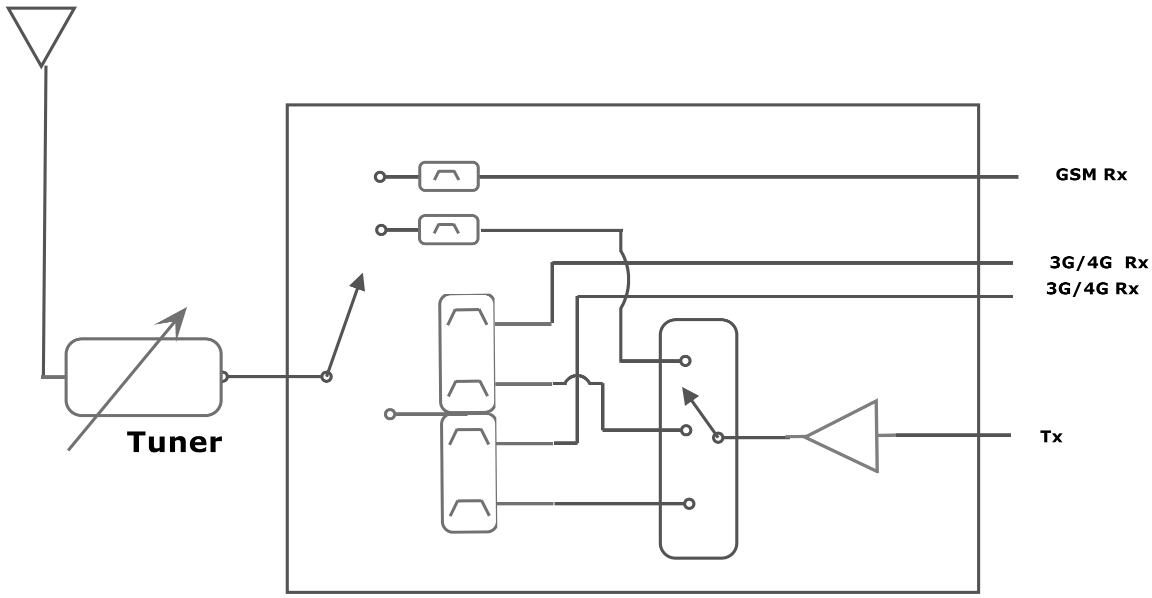


Figure 28: Block Diagram for low-band antenna tuning with lo-lo CA

Source: Mobile Experts

This approach has been used for mid-to-high bands. It requires more careful antenna design and careful selection of a tap point for a tuning element….but this has all been achieved successfully. Low band antennas have not required this approach so far, but over time we anticipate that lo-lo Carrier Aggregation scenarios will arise and we will have multi-resonant antennas for low bands as well as high bands in the same phone.

Impedance Match Tuning

Impedance tuners are aimed at the premium tier of the market, as most of the improvement in performance is not perceived in conducted tests anyway, making low-tier handset suppliers less interested in the technology. Qualcomm's closed loop impedance tuning approach has been pretty successful, with adoption of their second generation tuner in multiple premium handsets.

Closed-loop tuning involves couplers to sense the reflected RF power, adapting the antenna impedance match dynamically to maintain the best match. The optimal match varies with changing load conditions (holding a smartphone next to your head or near a metal surface). Note that Huawei uses an open-loop impedance tuning technique while Samsung uses closed-loop tuning.

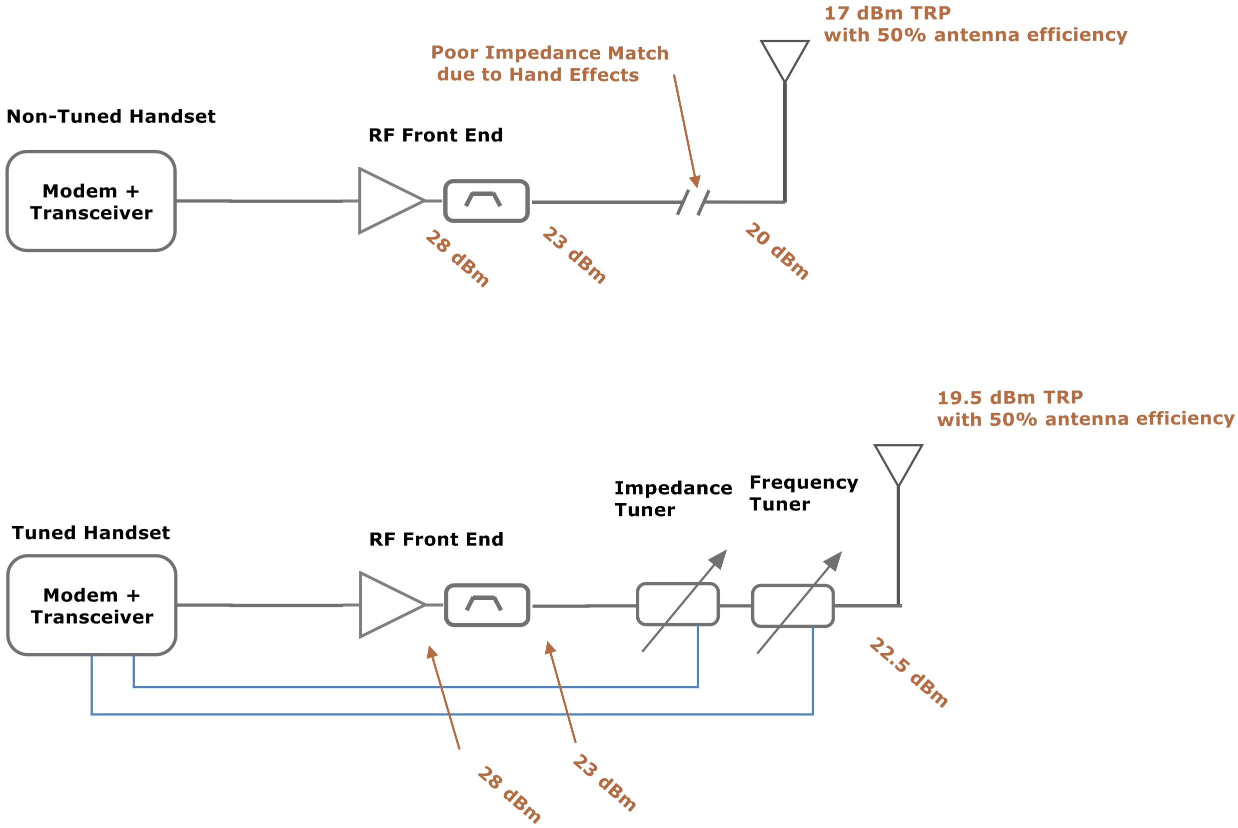


Figure 29: Typical Impact of Closed-Loop Tuning

Source: Mobile Experts

Impedance-match tuning remains at low adoption levels, because the primary impact is not on the conducted performance of the handset, but on real-world radiated performance. Handset OEMs generally design the handset to work best for certification testing, not for real-world performance, so an extra component to improve the RF chain is not used in many cases.

The above figure illustrates how this will work in real life. The conducted performance of the two handset diagrams shown would be identical, but the handset including a tuner would adjust for hand effects, giving essentially 2.5 dB higher TRP. This means that the LTE base station would direct the handset to turn down its power by 2.5 dB, saving power. This translates directly into longer battery life. For this reason, we still believe that some premium smartphones will adopt impedance tuning over the longer term.

Market Shares/Design Wins

Qorvo leads the market currently, with multiple SOI switches several smartphone platforms. Skyworks, RF360 (Silanna), and others also provide SOI switches for a well established segment in low-band aperture tuning.

Cavendish is the interesting supplier to watch. Supplying MEMS-based tuners, Cavendish started with the smaller Chinese OEMs, but has proven excellent reliability and great performance, and this year they have dramatically grown their revenue and market share by penetrating top-tier customers in volume. Cavendish doesn't have any serious competition in MEMS devices because the other suppliers dropped out.

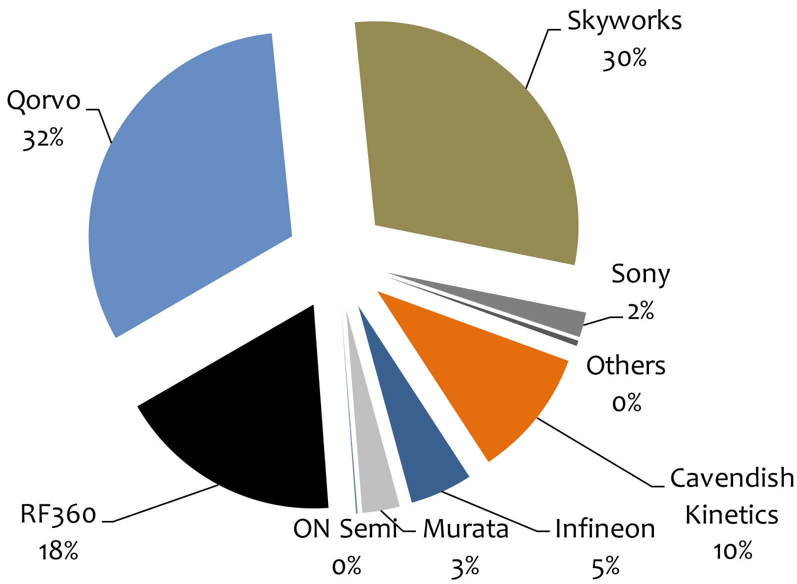


Chart 37: Market Shares, Aperture Tuning Devices (switches and tuners), 2018

Sources: Mobile Experts

Market shares for impedance-match tuning follow the modem vendors. Qualcomm modems will be paired with RF360 impedance tuners, and Intel or other modems will use third-party RF vendors such as Qorvo or Cavendish.

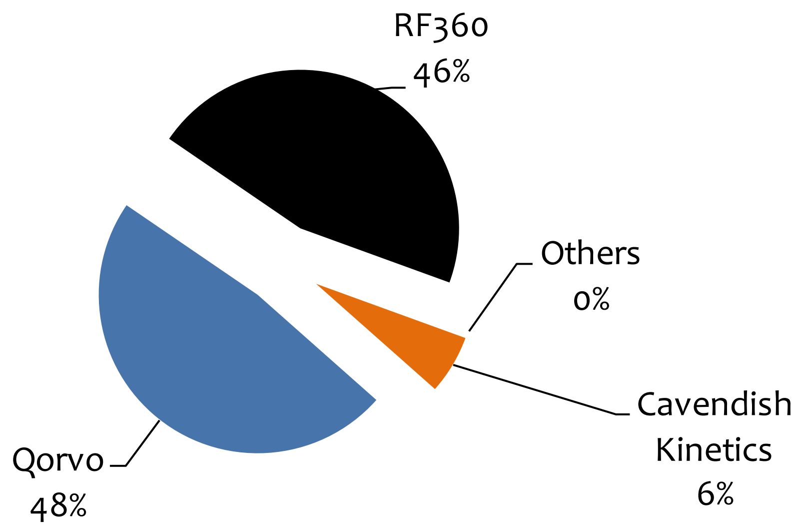


Chart 38: Market Shares, Impedance Tuners, 2018

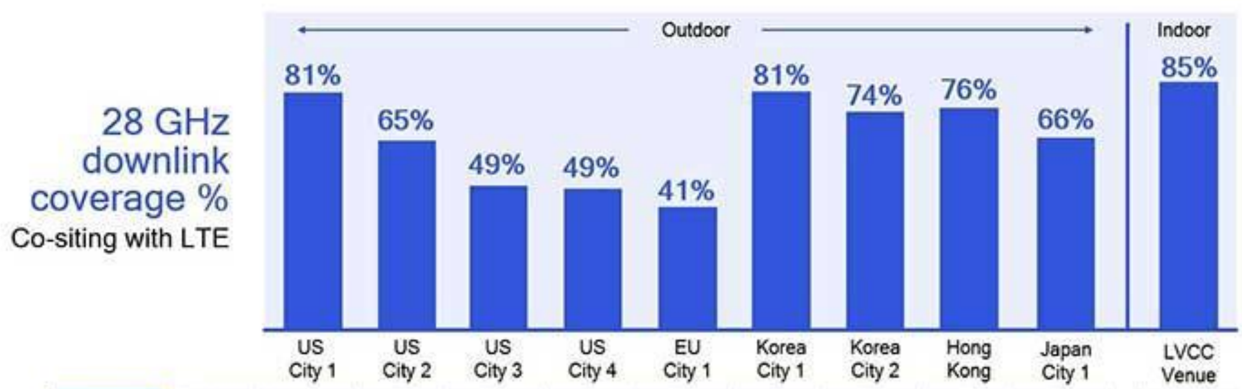
Sources: Mobile Experts.

10 MILLIMETER WAVE RFFE

The first 5G mm-wave networks are now on the air, and in fact the first smartphone with 5G NR at 28 GHz has been released (the Motorola 5G MOD). Initial reports of mobile performance in the field are HORRIBLE for the smartphone form factor, but performance of fixed-wireless CPEs looks pretty good. This market is not off to a good start.

At least 10 handset models are expected to be released in late 2019, using Qualcomm modems and RF Front End chipsets. The semiconductor devices work just fine; the problems come at a system level as the mm-wave channel is highly variable in a mobile urban environment.

Qualcomm has released simulations that predicted good coverage for the 28 GHz downlink, co-sited with LTE base stations. The US 5G NR networks that have been launched so far use 28 GHz base stations that are close to the street level, and spaced closely so that coverage should be even better than indicated below.



Site density (per km2)		US City 1	US City 2	US City 3	US City 4	EU City 1	Korea City 1	Korea City 2	Hong Kong	Japan City 1	LVCC Venue
	Total	48	36	32	31	28	41	31	39	37	134 antenna locations
	Macro	0	8	15	14	7	33	31	39	37	
	Small	48	28	17	17	21	8	0	0	0	

Figure 30. Dense LTE networks get good Downlink coverage at 28 GHz

Source: Qualcomm

However, the actual performance so far for early devices has been flaky, with users indicating that the 5G logo 'flickers' on the screen of the handset. In other words, users believe that the 5G signal is not stable enough to provide sustained performance.

Fixed CPEs and mobile hotspots for 28 GHz and 39 GHz

The earliest deployment of mm-wave used Verizon's proprietary 5G TF format (really an extension of the OFDM used for LTE), with CPEs and base stations made by Samsung and

Ericsson. Because of the lack of complete standards, this network involved Ericsson base stations with Ericsson CPEs and Samsung base stations with Samsung CPEs. Verizon deployed a handful of cities with this configuration but has now stopped investing in 5GTF, focusing its efforts on 5G NR.

In the CPE form factor, we expect large numbers of antennas to be used, with as many as 8 sub-arrays (4 dual-polarized antennas per sub-array). The total of 32 antennas results in higher EIRP, overcoming low output power from the RF amplifier with additional PA units as well as beamforming software to create a high-gain antenna array out of all sub-arrays.

Figure 31. Outdoor and indoor CPE products for 5G at 28 GHz

Source: Samsung

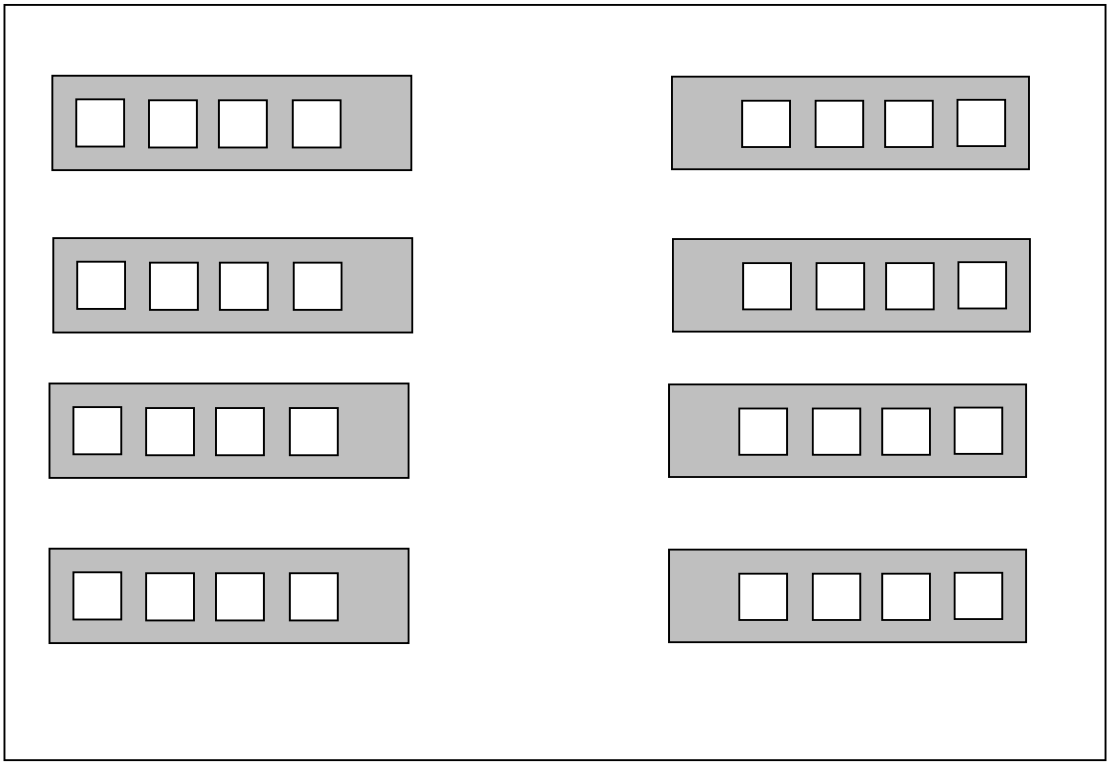


Figure 32. Possible Configuration of RF Sub-arrays for a 5G CPE at 28 GHz

Source: Mobile Experts

Mobile Devices: Tablets and Handsets at 28 GHz

In handheld devices, there are two major disadvantages compared with the CPE application:

1. In tablets or handsets, the system engineer must conserve power because the unit is expected to work on batteries. The smartphone is an extreme example of this, as smartphone customers are jealous of their battery life and will react strongly to features that reduce longevity. The mm-wave sub-arrays have two impacts on the battery: first, they reduce the space available for the battery inside the phone because multiple sub-arrays are required and they require a small but finite space. Secondly, the RF amplifiers at 24-40 GHz are not efficient, so operation of the radio will require a high level of peak power to get useful transmissions.
2. The number of sub-arrays in a handheld device will be much lower than the number in a fixed CPE. Where 32 dual-polarized antennas will be typical in the CPE (with higher numbers in some cases), we expect to see 12 dual-pol elements or three sub-arrays in most 5G mm-wave smartphones. This means that the total conducted RF

power will be lower by almost 2/3, and also the expected antenna gain will be much lower.

3. The biggest drawback of a handheld form factor is that the user's hand will cover some of the antenna elements. Thus, even though 12 dual-pol antennas may be available, a large number of these could be covered by the user's hand at any time. That means that the EIRP is reduced even further in the uplink, and a closed-loop TDD link will be difficult to maintain.

Figure 33. Motorola Moto 5G MOD smartphone with 28 GHz radio

Source: Motorola

Mobile Devices: Mobile hotspots

We believe that the industry is likely to compromise between the high performance of CPEs and the portability of smartphones. In a mobile hotspot, a large number of antenna elements can be used because the size pressures of the smartphone can be more relaxed. Similarly, the battery can be larger than space allows in a smartphone size.

Also, many people are willing to use a mobile hotspot in "plugged in" mode, taking away some concerns about battery life.

But the most important advantage of the mobile hotspot is that typical use would be as a desktop device, not a handheld device. Removing the user's hand from the case of the device allows the radio link to have much better performance and more predictable outcomes.

RF implementation at mm-wave bands

In the mm-wave bands, a high level of integration between the RF section (switch, PA, LNA, up/downconverter) and the antenna will be critical. There's no hope of connecting separate antennas to discrete RF components in a cost-effective way.

The mm-wave radio will be highly integrated, with very close proximity for the antenna elements, filters, amplifiers, and data converters. Early concepts using GaN or SiGe amplifiers have faded, as the cost profile of any RF subassembly would be much too high for a consumer product. Despite lower power output, silicon CMOS RFICs are used for the RF functions, including the PA, switch, LNA, and up/downconverter. We believe that the product on the market now offers downconversion to roughly 6-10 GHz for transport to a centralized RF transceiver.

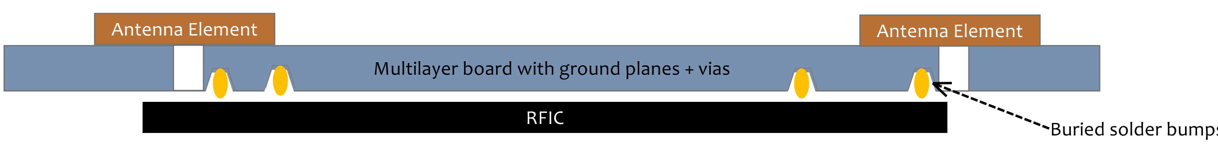


Figure 34. Cross section of a silicon 5G radio/antenna array

Source: Mobile Experts

At this point in time, Qualcomm is the only supplier providing mm-wave front ends for commercial devices. Intel has dropped out of the modem market, so we expect them to back away from providing mm-wave RF front ends as well. Huawei is likely to develop its own product, but other participants are unknown at this time.

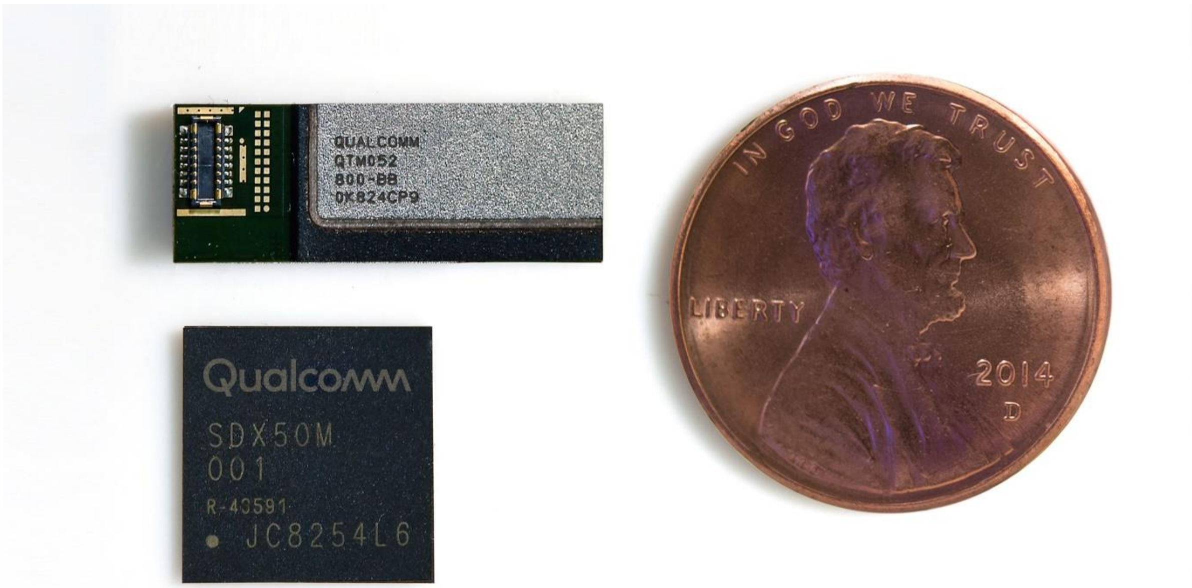


Figure 35. Qualcomm's QTM052 mm-wave sub-array

Source: Qualcomm

11 OUTLOOK FOR MOBILE TERMINALS

Big-Picture Outlook

Things are getting weird in the smartphone market. Growth has stalled, so the OEMs are coming out with phones at $1500 and higher, as well as foldable phones and other features to try to change the rules of the product category. It's clear that strong consumer growth is finished, although 5G may spark a small resurgence for a short time.

The handset suppliers are hoping that the 5G cycle will drive a lasting wave of replacement handsets, but we are skeptical. So far we don't see a compelling reason for the end user to buy a 5G phone. The benefits of 5G accrue to the mobile operator, not to the end user. In the end, we expect the 5G wave to provide a mild stimulus to the smartphone market. Bigger growth will be seen in the IoT market and possibly with new 5G hotspots or other devices.

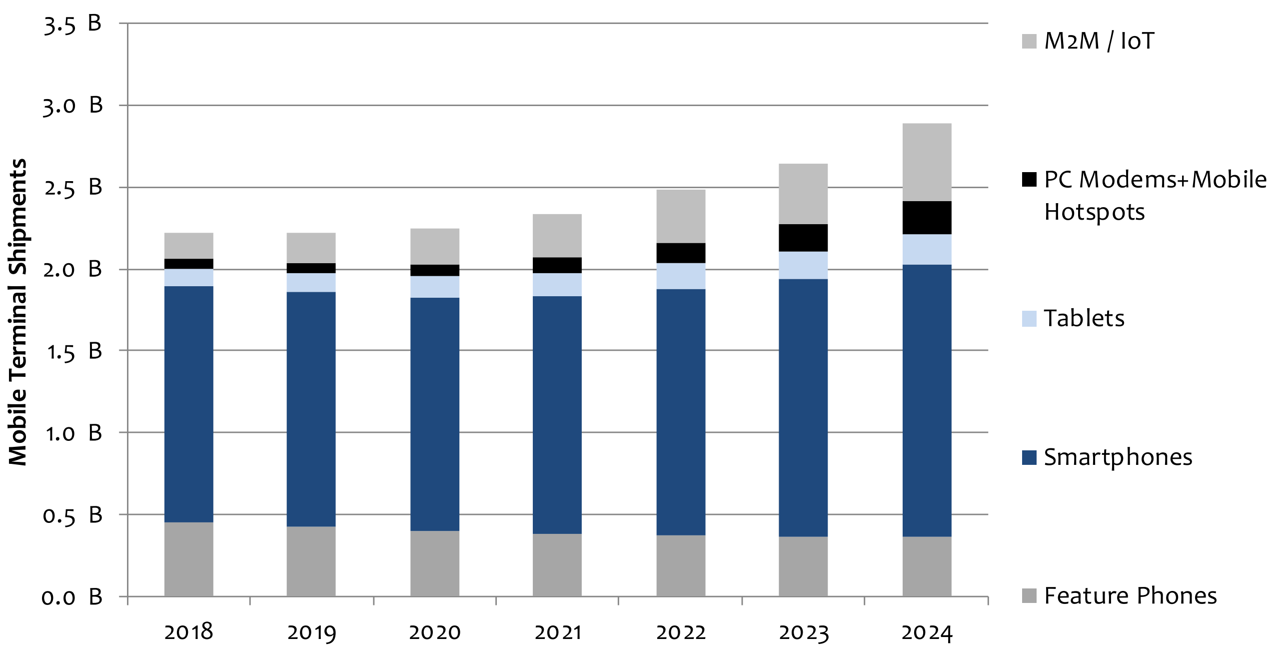


Chart 39: Mobile Terminal Forecast, by terminal type, 2018-2024

Source: Mobile Experts

The Cellular IoT market has several growth factors behind it. We've written much more detail on this market in a separate 80-page study. Automotive, asset tracing, industrial, and possibly health care applications will be the leading sectors, with automation in the enterprise driving significant quantities. C-IoT devices are getting more complex, with multiple bands and modes in some units, but in general these will be cheap devices.

Overall, NB-IoT and Cat-M devices will constitute most of the growth in cellular IoT. The total number of C-IoT devices will expand to 480 million in 2024.

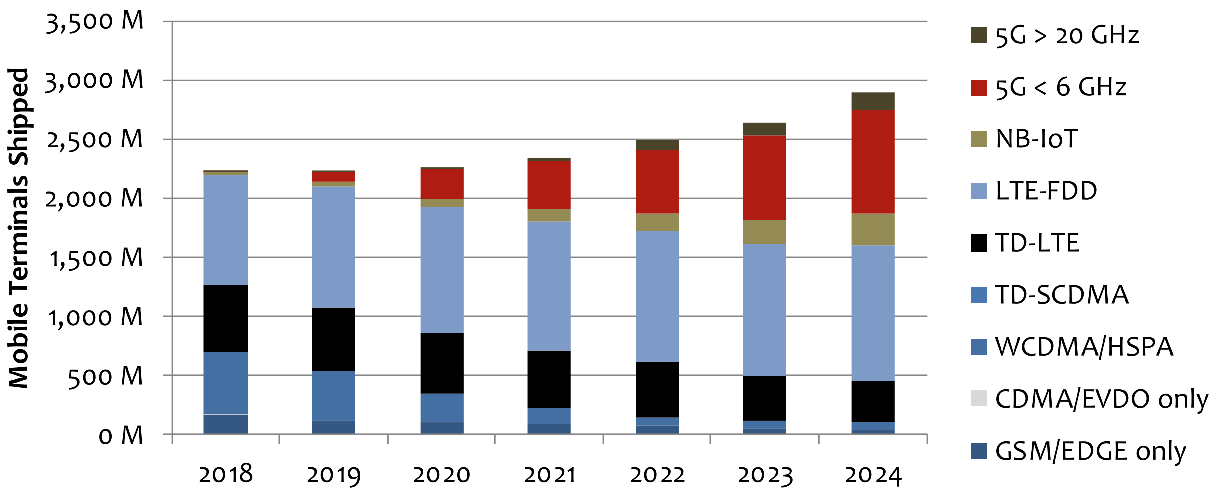


Chart 40: Mobile Terminal Forecast, by primary air interface, 2018-2024

Source: Mobile Experts

Feature Phone Outlook

The feature-phone market shrank quickly as smartphones grew, but a small stable element of the market remains and may be with us for a long time. Low-cost suppliers with $10 feature phones are in no danger of competition from smartphone vendors… we believe that this segment of the market will flatten out at about 350 million devices per year, as over a billion people still would like to buy a phone, and another 2 billion are involved with a replacement cycle on feature phones already.

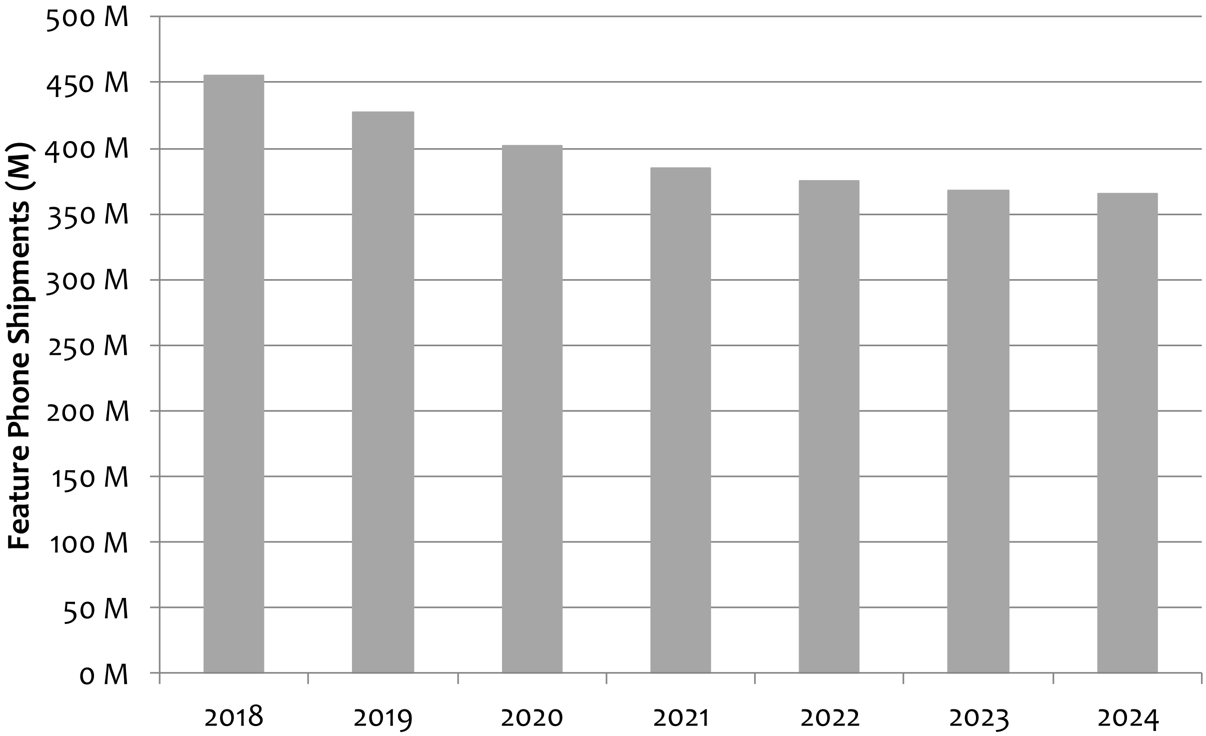


Chart 41: Feature Phone Forecast, by primary air interface, 2018-2024

Source: Mobile Experts

Smartphone Outlook

Smartphone sales are flat with replacements of old phones extending over a longer time this year. There's a possible boost coming up when 5G smartphones come onto the market in each country. However, until new apps appear that truly require 5G, we don't expect a large impact.

Within the smartphone segment, there are some positive trends:

- Premium tier smartphones will add 5G in the 3-4 GHz bands this year.
- Mid tier smartphones cost between $200 and $500 will adopt CA but the combinations are simpler, with a lower band count in some cases. The mid-tier is moving into 4x4 MIMO over time in the high bands.
- Entry level smartphones cost less than $200 and generally have fewer bands and no MIMO/CA support.

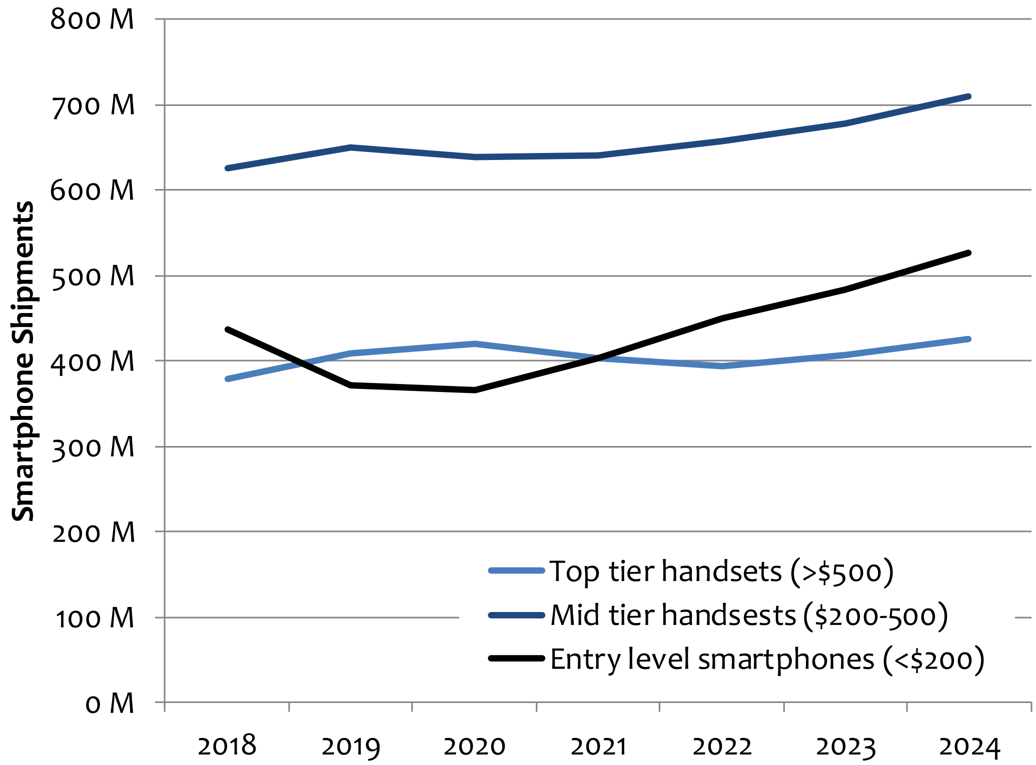


Chart 42: Migration from Entry-Level to Premium Smartphones, 2018-2024

Source: Mobile Experts

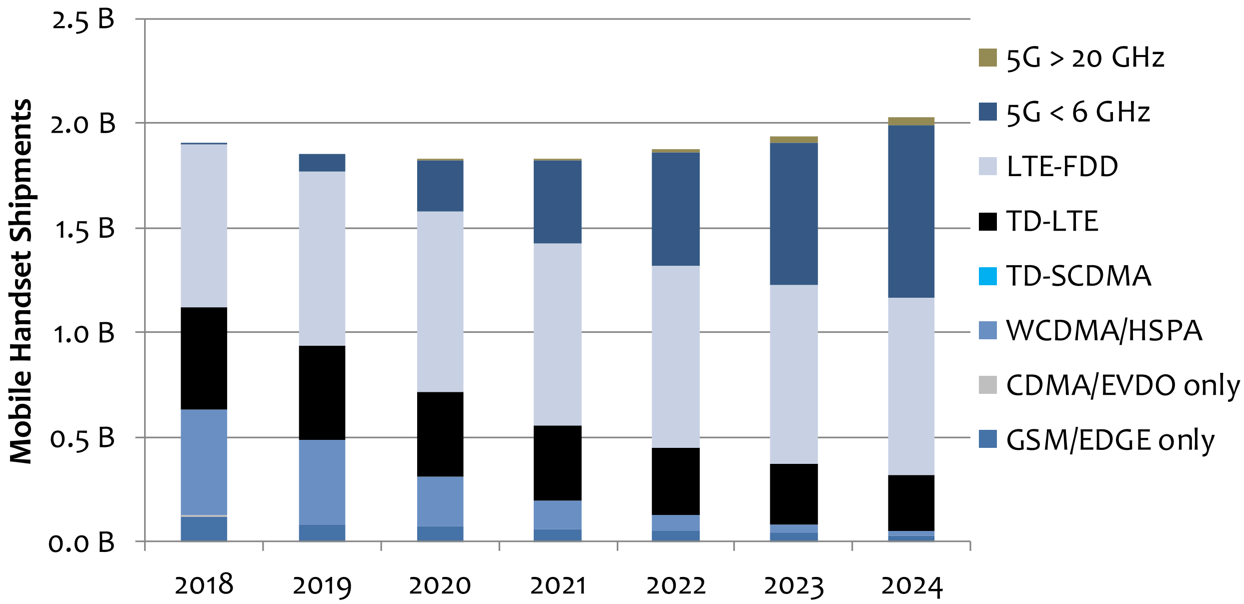


Chart 43: Mobile Handset Shipments, by Air Interface Standard, 2018-2024

Source: Mobile Experts

Overall we expect smartphone growth at only 1% CAGR for the next five years, reflecting basically flat sales and lengthening replacement cycles, balanced by new 5G demand and new customers in emerging markets.

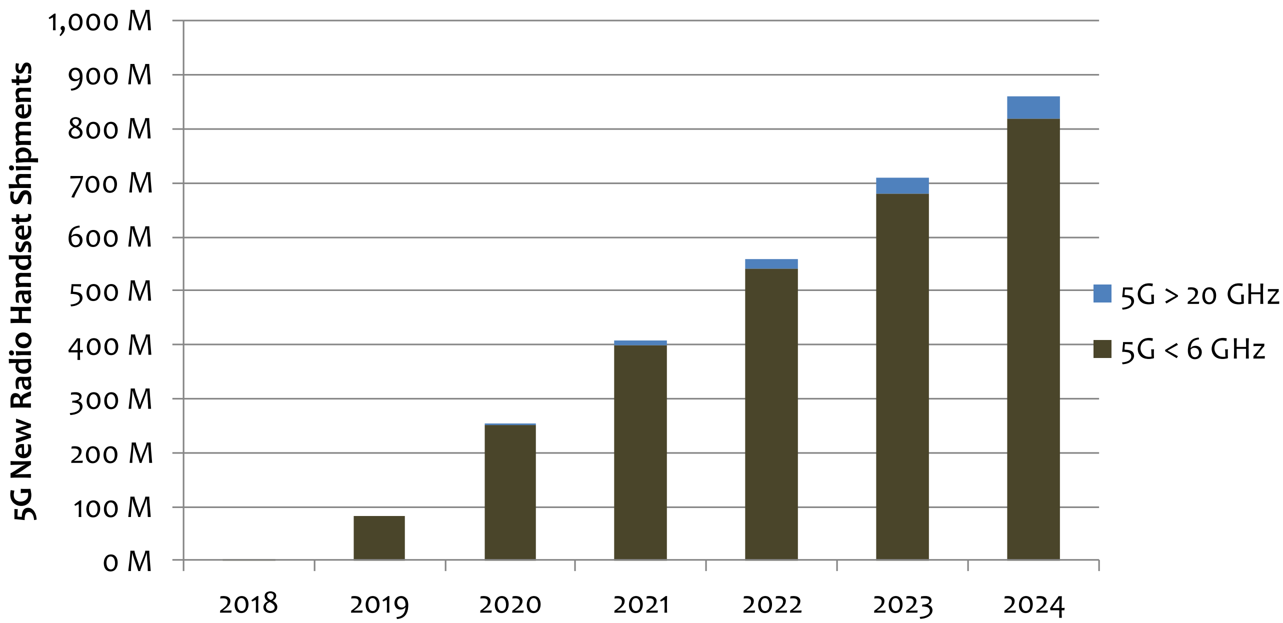


Chart 44: 5G Handset Shipments, sub-6 GHz and mm-wave, 2018-2024

Source: Mobile Experts

Tablet Outlook

As people become more comfortable with using LTE/5G as a primary connection, we see that many people don't even turn on Wi-Fi anymore. We expect tablets to increasingly adopt LTE and 5G. One reason for this is that we expect the "unlimited" plans to become more truly unlimited, as operators realize lower cost in 5G and try to motivate people to use their 5G devices.

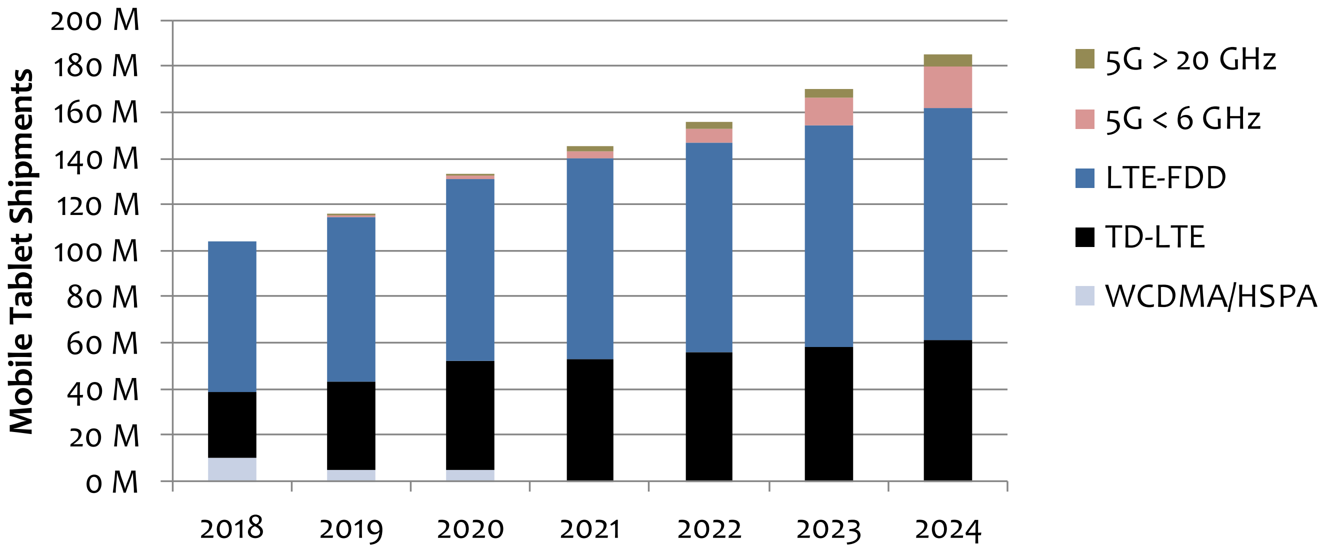


Chart 45: Forecasted Mobile Tablet Shipments, 2018-2024

Source: Mobile Experts

PC Modem and Mobile Hotspot Outlook

The PC and hotspot market has not been a big, exciting segment of mobile devices, but we expect that 5G mm-wave will bring more attention to the hotspot. Operators with 5G mm-wave networks will need to incentivize customers to use the mm-wave band, and most handsets will not support mm-wave. As a result, we expect AT&T and Verizon in particular to provide hotspots and CPEs for nomadic and fixed customers to easily utilize the mm-wave spectrum.

Note that this year we have included fixed CPEs as well as truly mobile hotspots, because the US CPE market has migrated over to 5G NR.

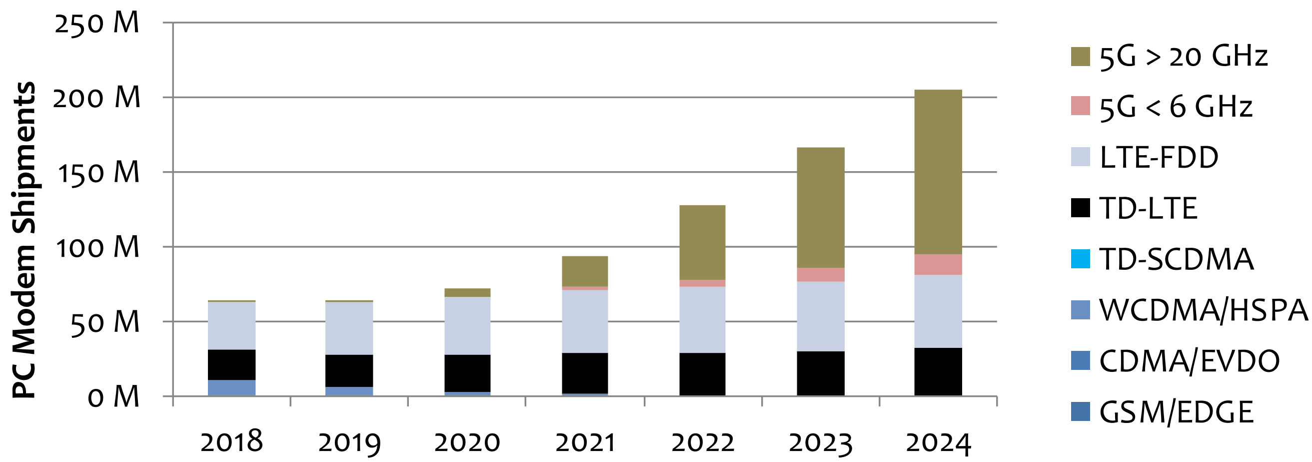


Chart 46: Forecasted PC Modem and Hotspot Shipments, 2018-2024

Source: Mobile Experts

Cellular IoT Devices

We're tracking more than 13 different variations of Cellular IoT, from old GPRS and CDMA 'M2M' devices to more optimized Cat-M and NB-IoT devices. Overall, growth will be solid in this area, with substantial unit growth coupled with rising RF content in many devices as they shift to dual-mode, multi-band, or advanced features like Carrier Aggregation.

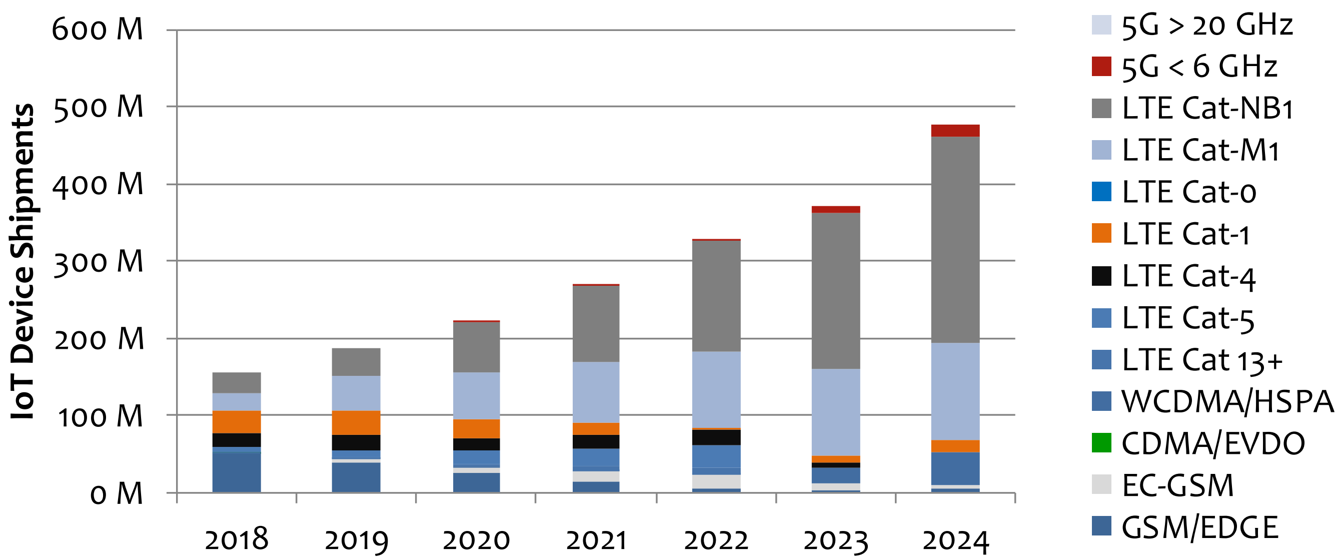


Chart 47: Forecasted M2M/IoT Terminal Shipments, 2018-2024

Source: Mobile Experts

12 RF FRONT END OUTLOOK

Shipment growth is still going okay, but price competition is significant in the market. We're now anticipating low growth in 2019 for the RFFE market, at only 1-2%. We have reduced our CAGR estimate through 2024 to a level of 2-4% RFFE growth, allowing for slightly higher growth in mm-wave, 4x4 MIMO, and new 5G bands during the 2020-2023 timeframe.

IoT content will also be responsible for a more significant portion of shipment growth in the 2021-2024 timeframe, as multi-band, multi-mode IoT devices reach meaningful numbers. Note that in 2020-2023 the smartphone RF content may slow down, but ongoing growth will continue due to IoT shipments.

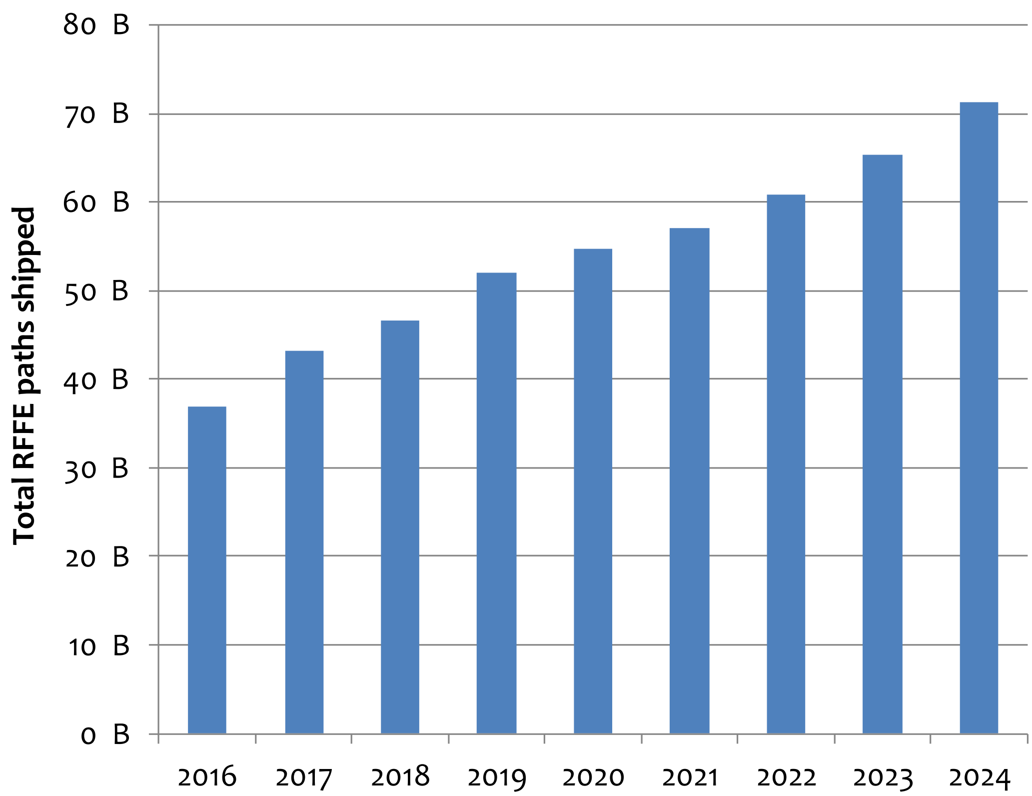


Chart 48: Forecasted RF Path Shipments, 2016-2024

Source: Mobile Experts.
NOTE: An RF Path represents the number of RF bands supported multiplied by the number of air interface modes in each band (uplink and downlink are counted together as one band)

The RF dollar content in various platforms is pretty flat, but adding mm-wave to a smartphone has a significant impact. Millimeter wave functionality will add about $13 of

RFFE BOM cost to a handset, and a more complex CPE/hotspot will carry an average RF BOM cost of $30 or more.

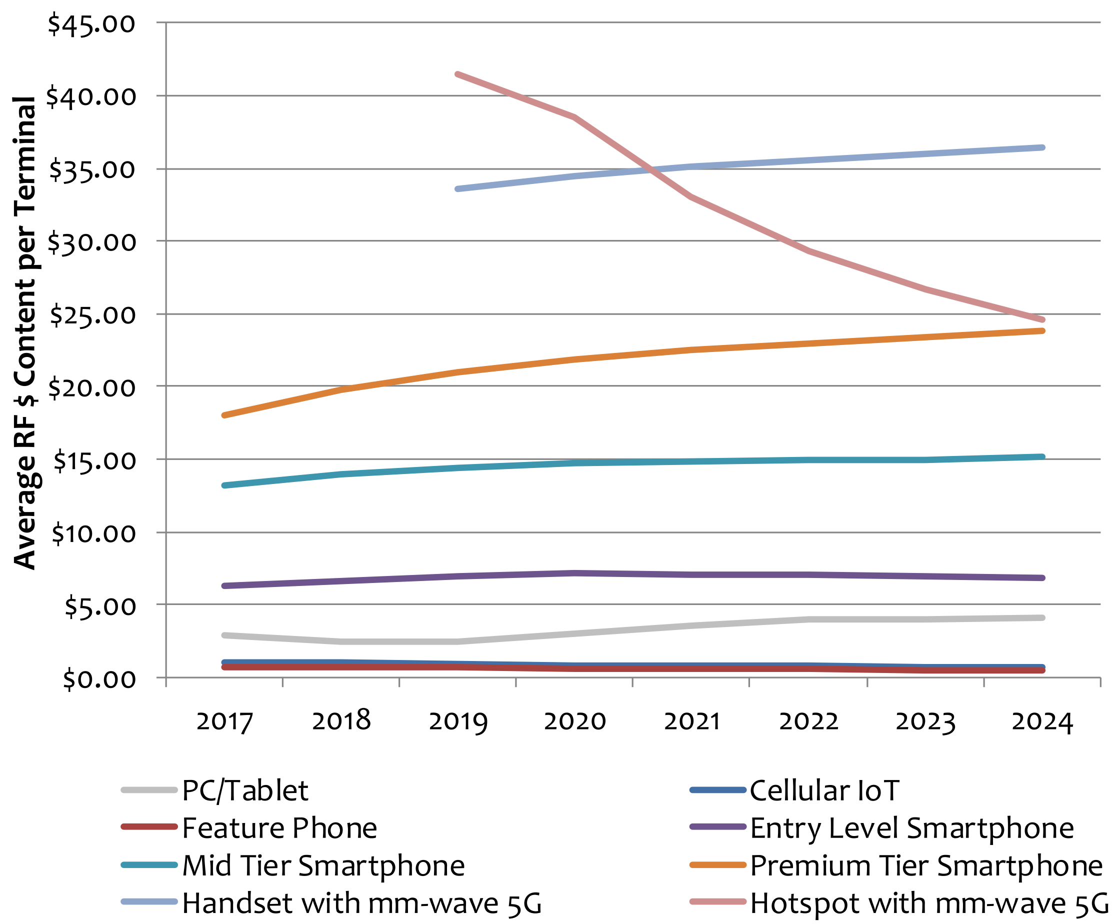


Chart 49: Forecasted RF Content in various terminal types, 2017-2024

Source: Mobile Experts.

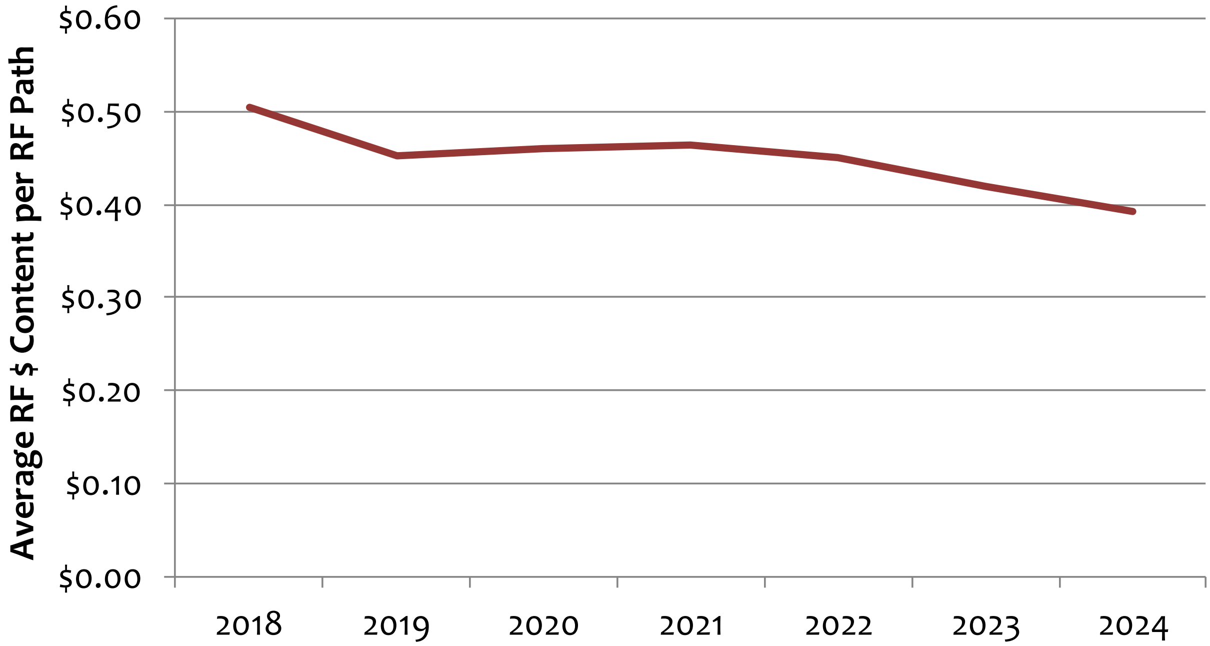


Chart 50: Forecasted RF Content per RF Path, 2018-2024

Source: Mobile Experts: Note: Excluding mm-wave paths.

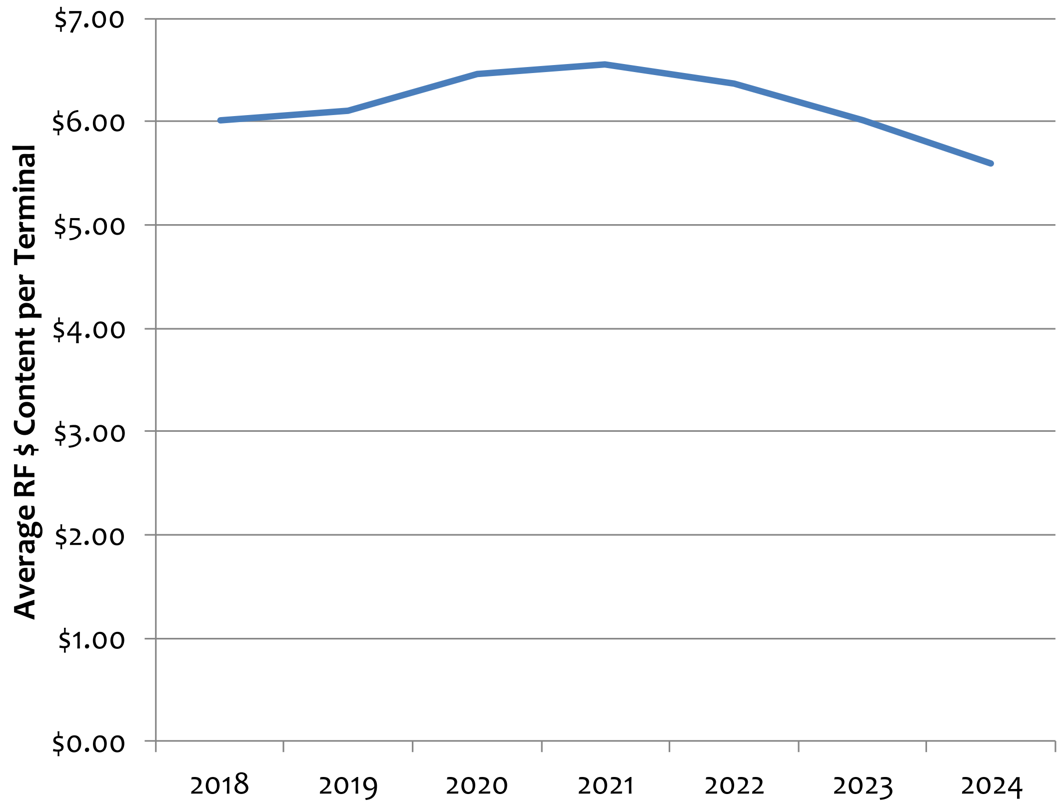


Chart 51: Forecasted RF Content per terminal, overall average, 2018-2024

Source: Mobile Experts

Filters and tuners will see ongoing growth in the RFFE, but other components such as amplifiers, have already peaked. A few other components (transfer switches, LNAs, and mm-wave) are new enough that growth will continue for a while, but some of these will also peak in the next few years.

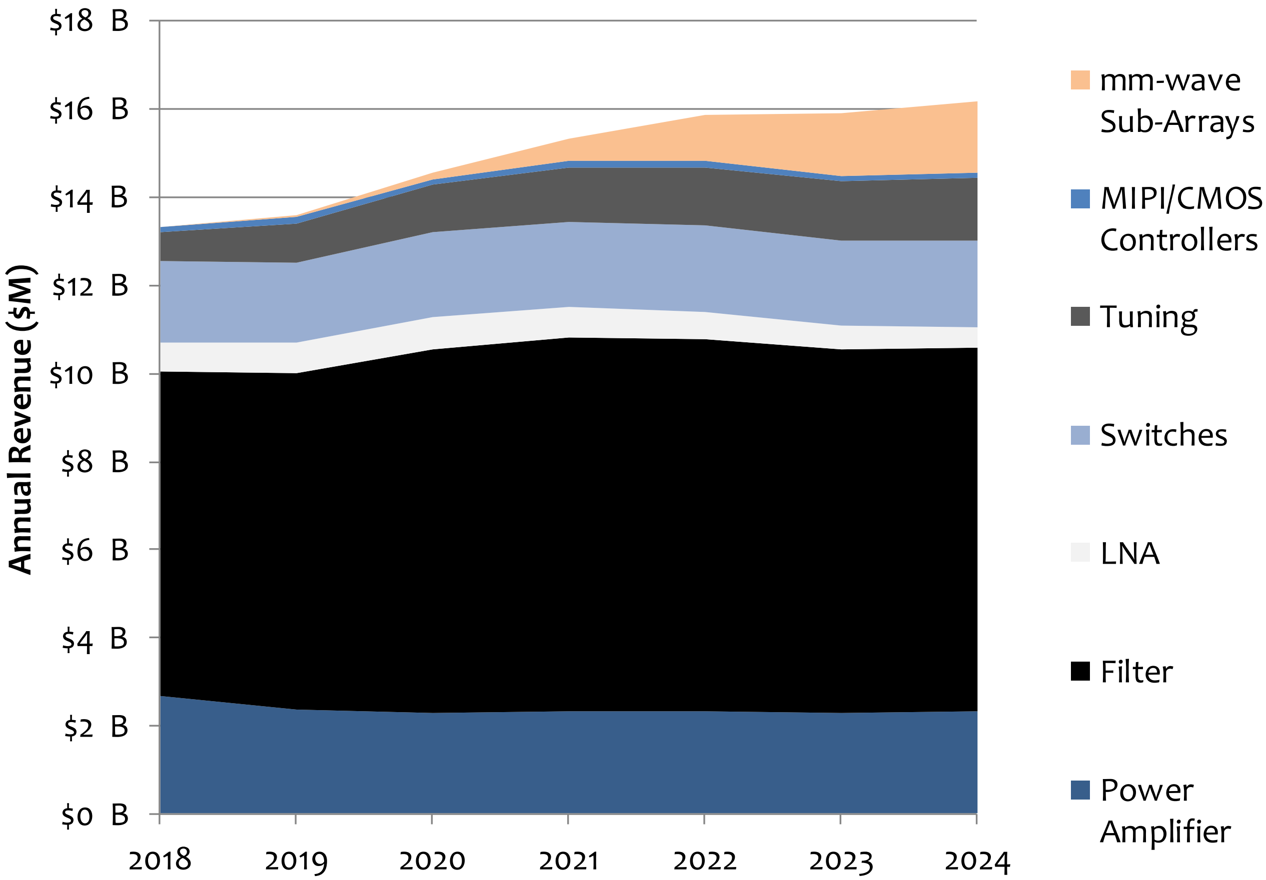


Chart 52: Forecasted RF Front End Market, by function, 2018-2024

Source: Mobile Experts

As we break down the market by the physical modules shipped, we see that CFEs have become a major segment of the market, along with discrete filters and diversity modules. Other modules play more minor roles in the total revenue picture. Millimeter wave sub-arrays will be the key to total RF growth in 2021-2024, as the other modules will not drive significant dollar growth.

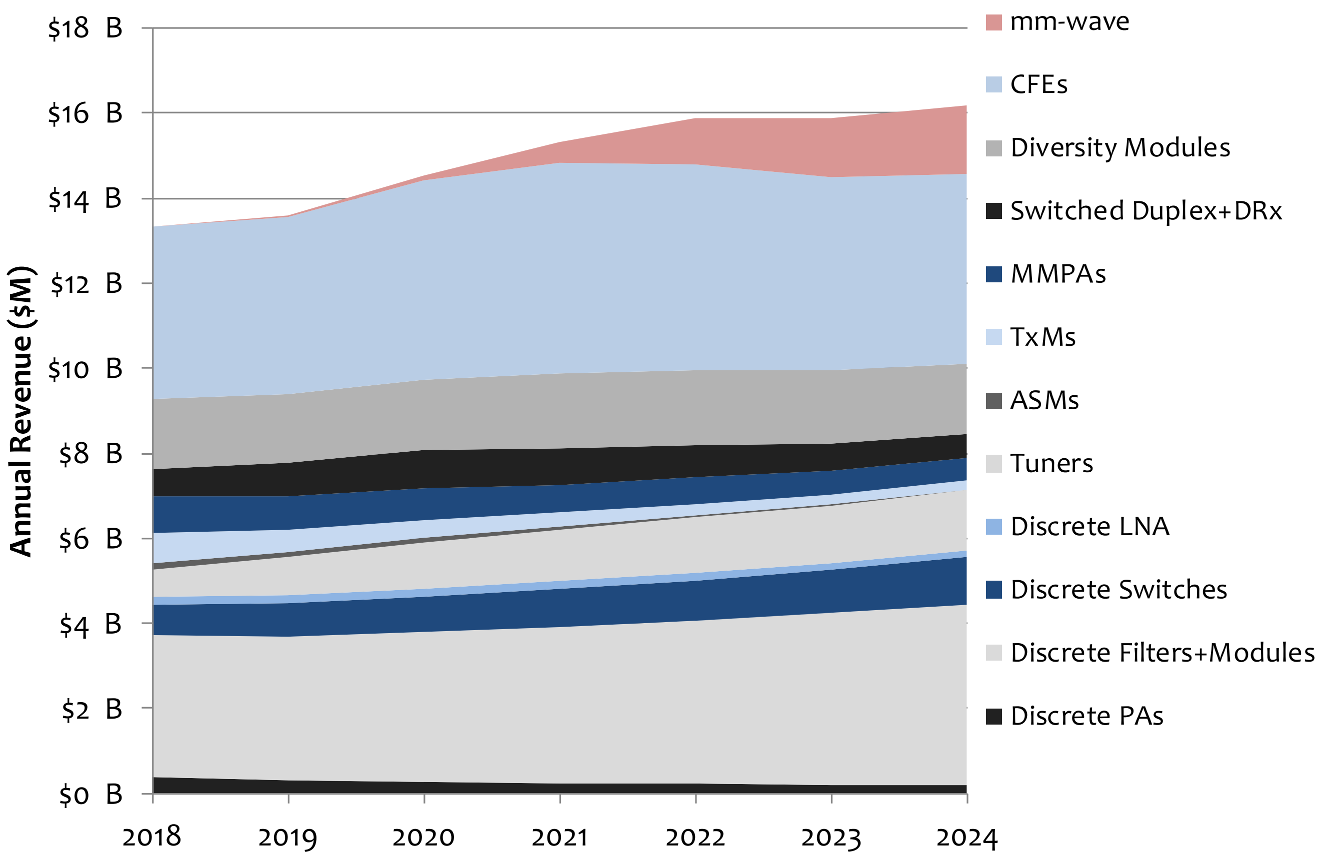


Chart 53: Forecasted RF Front End Market, by module type, 2018-2024

Source: Mobile Experts

The number of physical RF paths supported in the handset will continue to grow, as new bands and 4x4 MIMO come into play. At the same time, we expect real progress with uplink MIMO and growth in the number of modules/RF paths on the uplink side.

The following chart excludes mm-wave RF paths, because the huge numbers of antennas in the 28 GHz band will distort the picture. In the case of mm-wave, one terminal is likely to have 16 or 24 downlink RF paths and possibly similar numbers on the uplink side… but it's all supported by 3 modules, so we choose to count those differently.

It's notable that the premium handsets will keep growing in terms of the number of RF paths, but as IoT growth takes off, the overall average RF paths per terminal will flatten out and possibly drop.

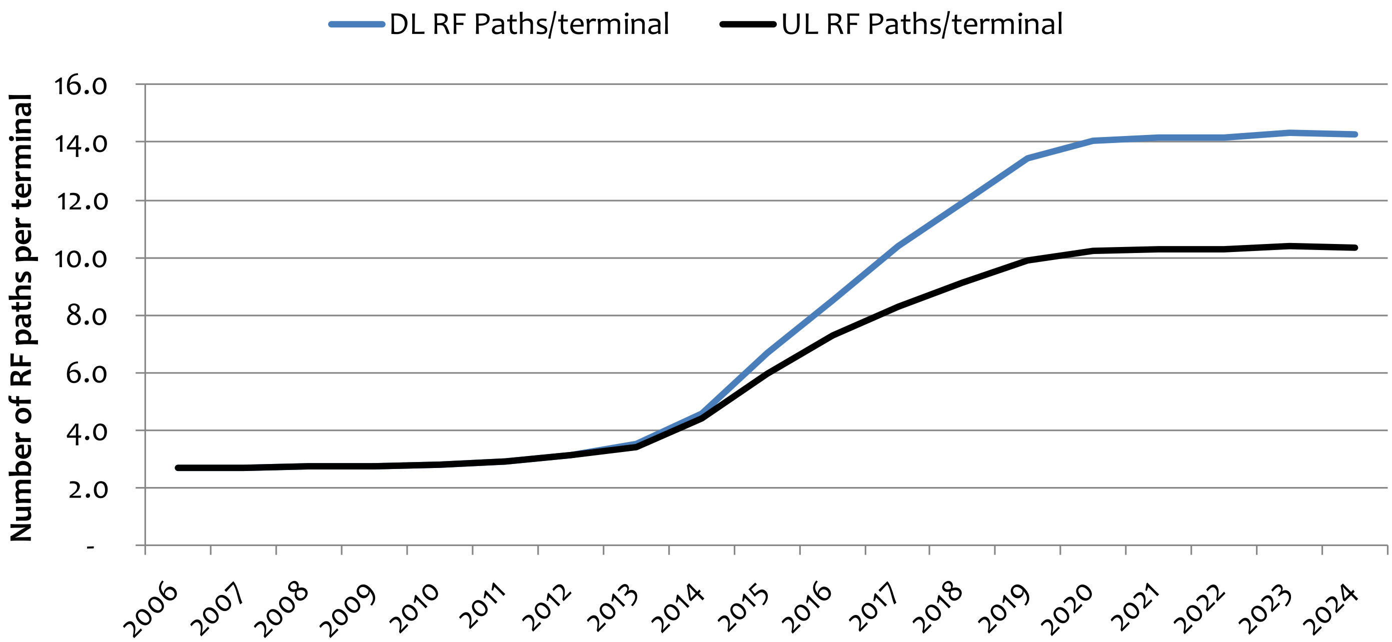


Chart 54: Uplink and Downlink paths per terminal, 2006-2024

Source: Mobile Experts. Excluding mm-wave RF paths

5G mm-wave Outlook

Over the past year, we have done a lot of background research to understand the motivation for 5G mm-wave networks. Mobile operators with high density of traffic in their urban networks are coming up on a crisis situation, where they will RUN OUT OF CAPACITY even when they fully utilize all bands below 6 GHz. For that reason, the mobile operators are extremely motivated in the USA, Korea, and Japan: they need to offload traffic to the mm-wave bands or they will experience poor service for customers.

The number of 5G RF paths will grow quickly because the number of RF paths per terminal will be high. Three sub-arrays per phone, with 4 elements per sub-array, translates into 12 downlink and 12 uplink paths per terminal. A CPE with six sub-arrays would use 24 paths in each direction.

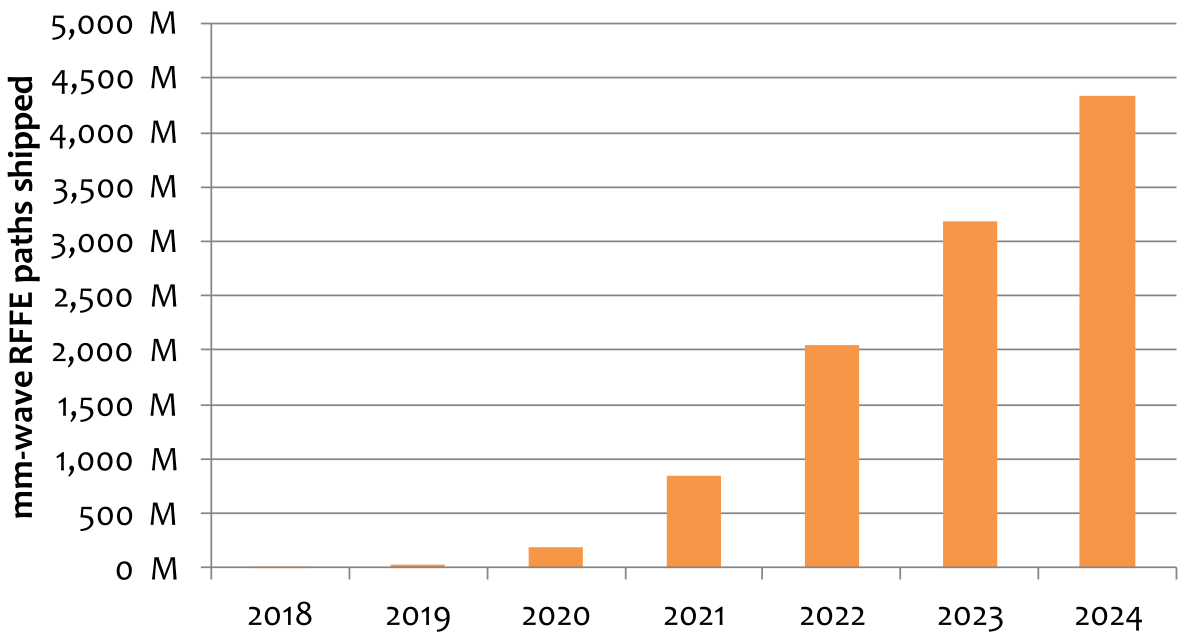


Chart 55: Forecast for mm-wave radio shipments in mobile terminals, 2018-2024

Source: Mobile Experts

Front End Module Outlook

For years, FEMs have represented the major growth element of the market, and discretes have been pushed down to the lower-tier handsets and other areas. At first glance, it would seem that FEMs would eventually take over the entire market. But that's not the case; FEMs are very useful for shrinking size and improving performance, but they sacrifice flexibility and therefore are not the best choice for smaller companies with simpler handset designs. At this point in time, we see the integrated market and the discrete market settling into a familiar pattern. FEM shipment growth will continue at about 5% per year but a net 5% price erosion will result in roughly zero growth for FEMs. (not counting mm-wave)

Table 5-1: FEM Shipment Summary, by FEM type	2017	2018	2019	2020	2021	2022	2023	2024	CAGR
ASM	249	233	209	199	130	87	60	32	-24%
TxM	1,069	907	749	625	507	427	390	411	-16%
MMPA	893	937	984	1,033	1,085	1,139	1,196	1,256	5%
Switched Duplexer Bank	285	315	385	460	450	410	370	330	3%
Diversity Module	1,425	1,512	1,610	1,762	1,958	2,126	2,203	2,266	8%
CFE	1,140	1,450	1,705	1,936	2,196	2,376	2,421	2,619	11%
Total FEM Shipments	**5,061**	**5,354**	**5,642**	**6,015**	**6,326**	**6,565**	**6,640**	**6,915**	4%

Table 5-2: FEM Revenue Summary, by FEM type	2017	2018	2019	2020	2021	2022	2023	2024	CAGR
ASM	178	157	132	113	67	40	25	12	-31%
TxM	908	702	529	415	317	253	220	218	-21%
MMPA	944	852	769	727	657	620	560	529	-8%
Switched Duplexer Bank	573	650	786	910	859	744	638	541	0%
Diversity Module	1,651	1,660	1,632	1,660	1,758	1,790	1,733	1,659	1%
CFE	3,727	4,047	4,150	4,678	4,942	4,849	4,542	4,463	2%
Total FEM Revenue	**7,981**	**8,069**	**7,999**	**8,502**	**8,599**	**8,297**	**7,719**	**7,424**	-1%

Figure 36: Front End Module (FEM) Shipment and Revenue Forecast, by Module Type, 2017-2024

Source: Mobile Experts
Not including mm-wave FEMs. See the MEXP-RFFE-18.xls spreadsheet for details.

We now have a wide variety of integrated modules, with every possible combination of switches, amplifiers, and filters. Mobile Experts defines a FEM as a module which includes two different functions (switches, amplifiers, filters), and counts single-function devices (like dual PA modules or passive filter banks) as part of the "discrete" market.

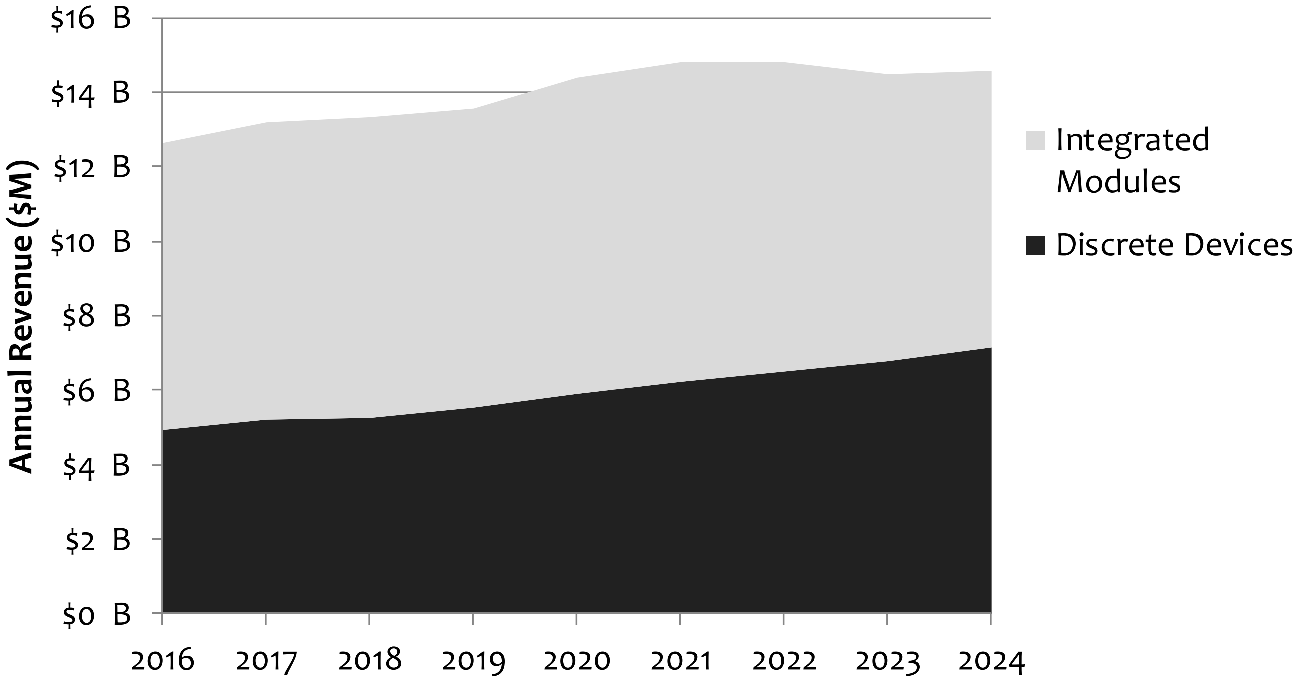


Chart 56: RF Revenue forecast, FEMs vs. discretes, 2018-2024

Source: Mobile Experts

Front End Modules include:

- Antenna Switch Modules (ASM): Combinations of antenna band switches or transmit/receive switches and filters for individual bands.
- Transmit Modules (TxM): Combinations of antenna switches and amplifiers Multimode Multiband Power Amplifiers: (MMPA) Adaptive amplifiers for multiple bands/modes combined with a band selection switch.
- Switched Duplexer Banks (aka FEMiDs): A bunch of duplexers with band selection switches.
- Diversity Modules: A bunch of bandpass filters with band selection switches and LNAs
- Power Amplifier-Duplexer Modules (PAD): A single-band PA tightly integrated with a duplexer.
- Complete Front Ends (CFE): A combination of amplifiers, switches, and filters to execute all RF functions for a block of frequency bands. LNAs are now becoming a part of these modules as well. (These are sometimes called PAMiDs or LPAMiDs). This category also now includes ‘LPAF’ devices such as LNA/PA/Fiilter/Switch modules for 5G at 3 GHz.

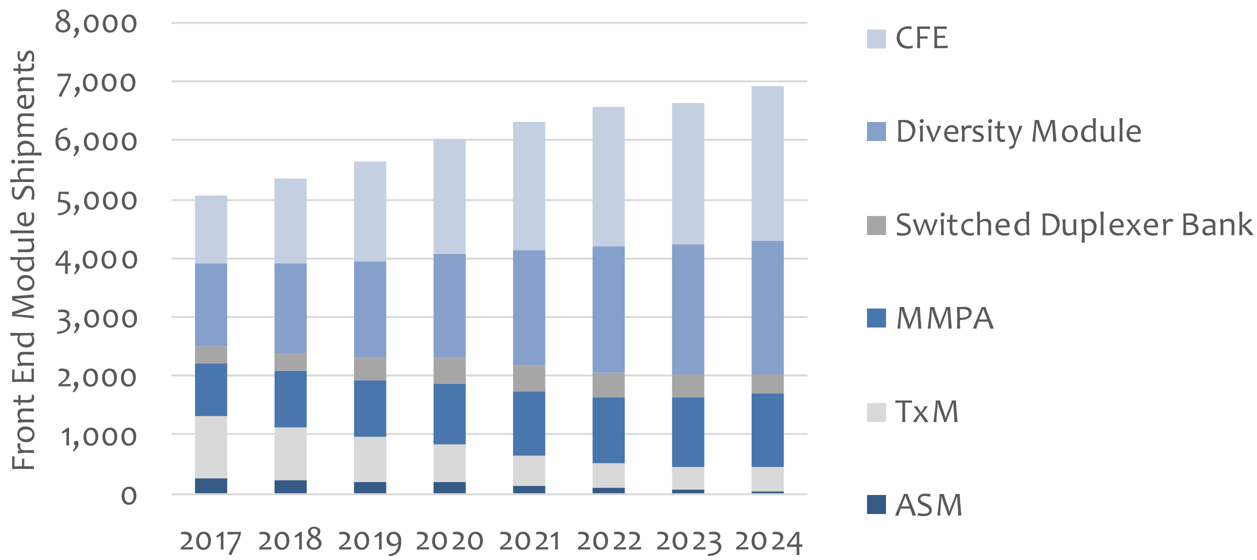


Chart 57: Front End Module (FEM) Shipments, 2017-2024

Source: Mobile Experts

The general trend in the market is still moving toward CFEs, although the driving forces are a little different. It's not simply second-tier companies buying CFEs to 'copy' Apple or Samsung. Instead we see the CFE adoption driven by availability of a modem/Envelope Tracking combination that leads to FEM integration. CFEs are still the best way to cram 20+ bands into a small size.

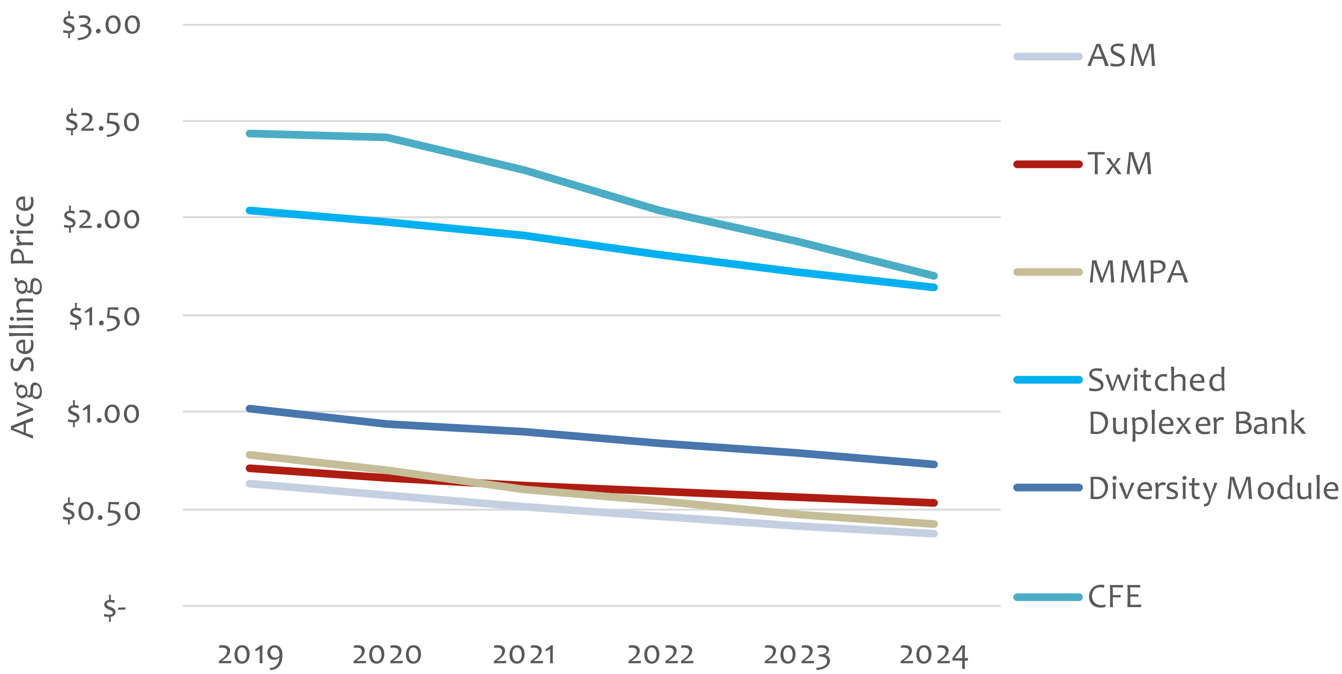


Chart 58: Front End Module (FEM) ASP, 2017-2024

Source: Mobile Experts

Qualcomm's entry into the market has resulted in some price pressure. We see it in the pricing for CFEs first, but the need for overall revenue makes the competition for diversity modules and discretes more cost-focused as well. These ASP reductions are an important part of the flat revenue picture overall.

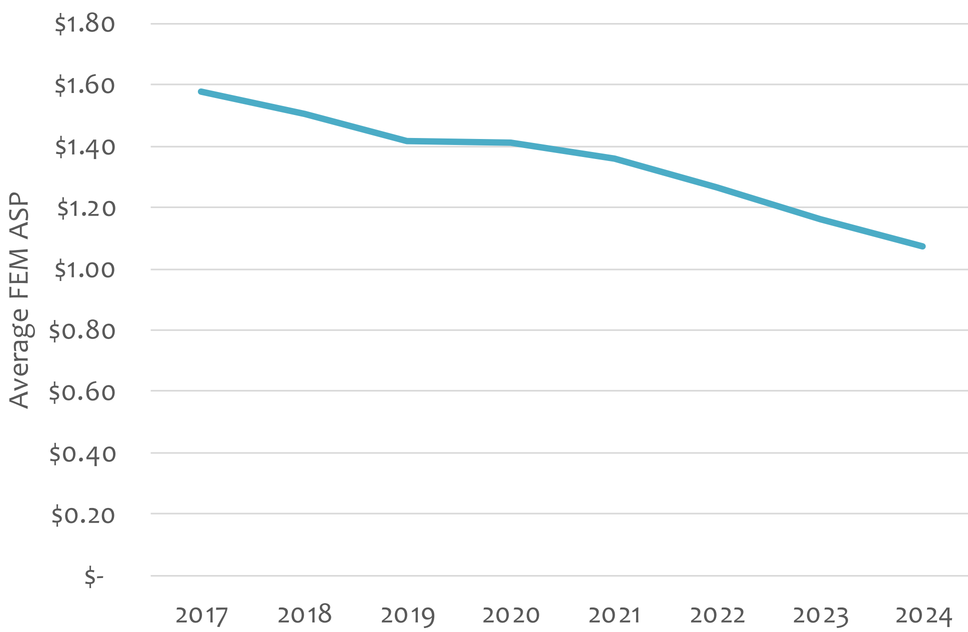


Chart 59: Front End Module (FEM) ASP, Average for all FEMs, 2017-2024

Source: Mobile Experts

The average price of all FEMs is an imperfect metric, but it shows that the overall complexity of RF products has stopped increasing so fast. The FEM ASP has peaked and is now steadily on its way downward. This may change, if multiple CFEs, diversity modules, or other products are grouped together to create a super-FEM at $4-5. Right now, we see a need for flexibility (UL MIMO, 4x4 MIMO, different bands) requiring a physical difference between FEMs such as Diversity Modules and CFEs.

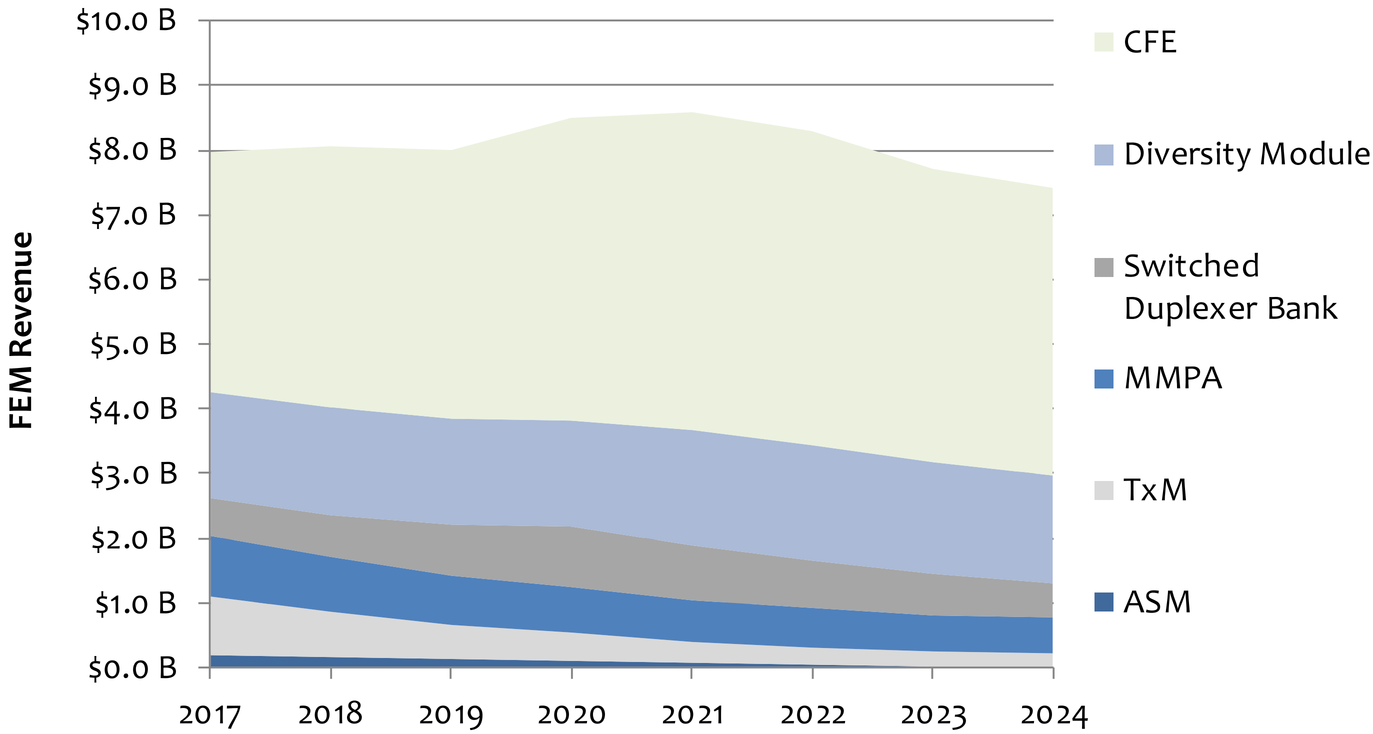


Chart 60: Front End Module (FEM) Revenue, 2017-2024

Source: Mobile Experts

Antenna Switch Module (ASM) Outlook

The old ASM architecture has been replaced now with the "Phase 2" or "Phase 3" architectures that involve Transmit Modules and MMPAs. This statement is true in the low end feature phones as well as more sophisticated smartphones with multiple modes. At this point we're just tracking the use of ASMs in low-tier LTE handsets that include filters and a few discrete PAs.

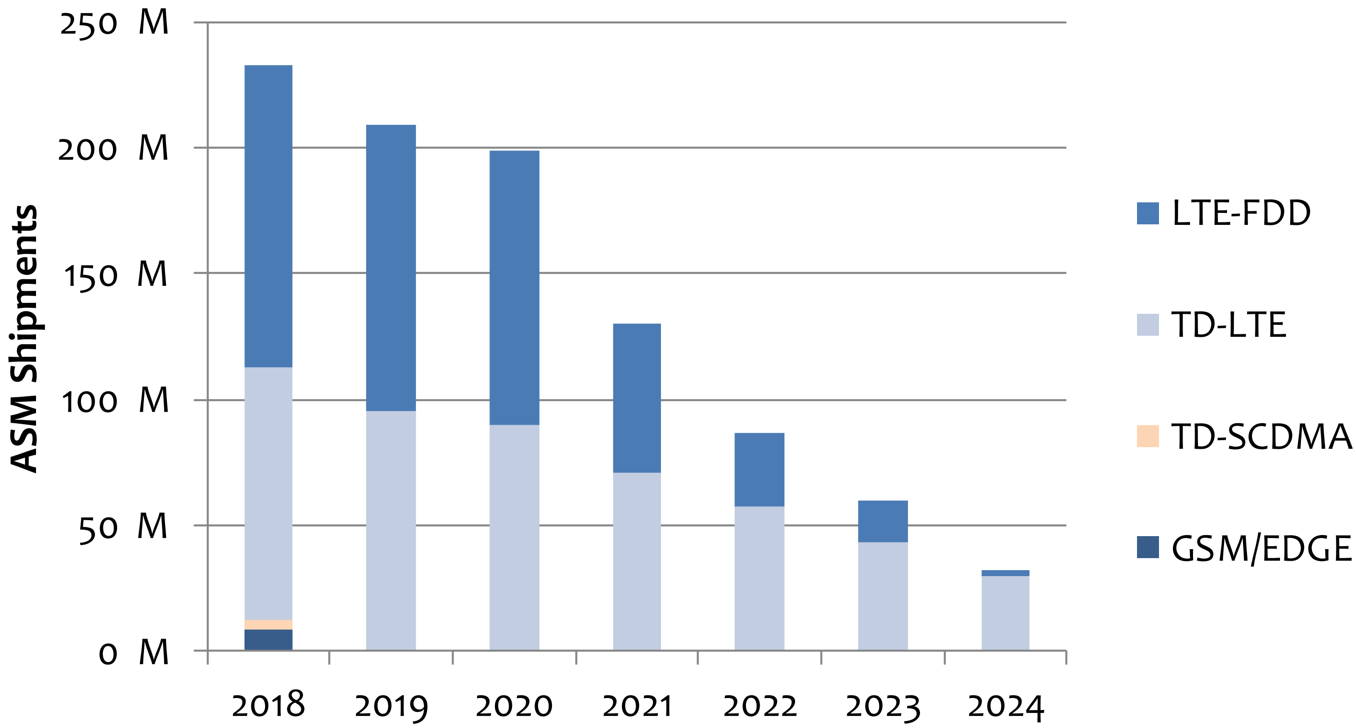


Chart 61: ASM Shipments, by air interface, 2018-2024

Source: Mobile Experts

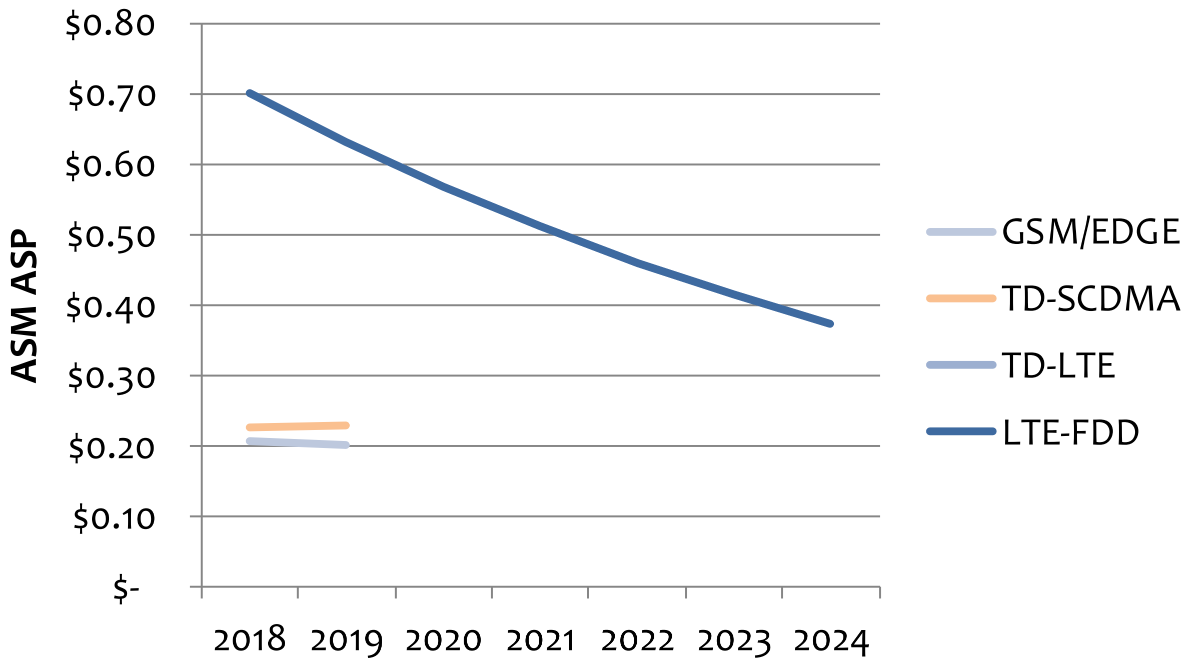


Chart 62: ASM ASP, by air interface, 2018-2024

Source: Mobile Experts

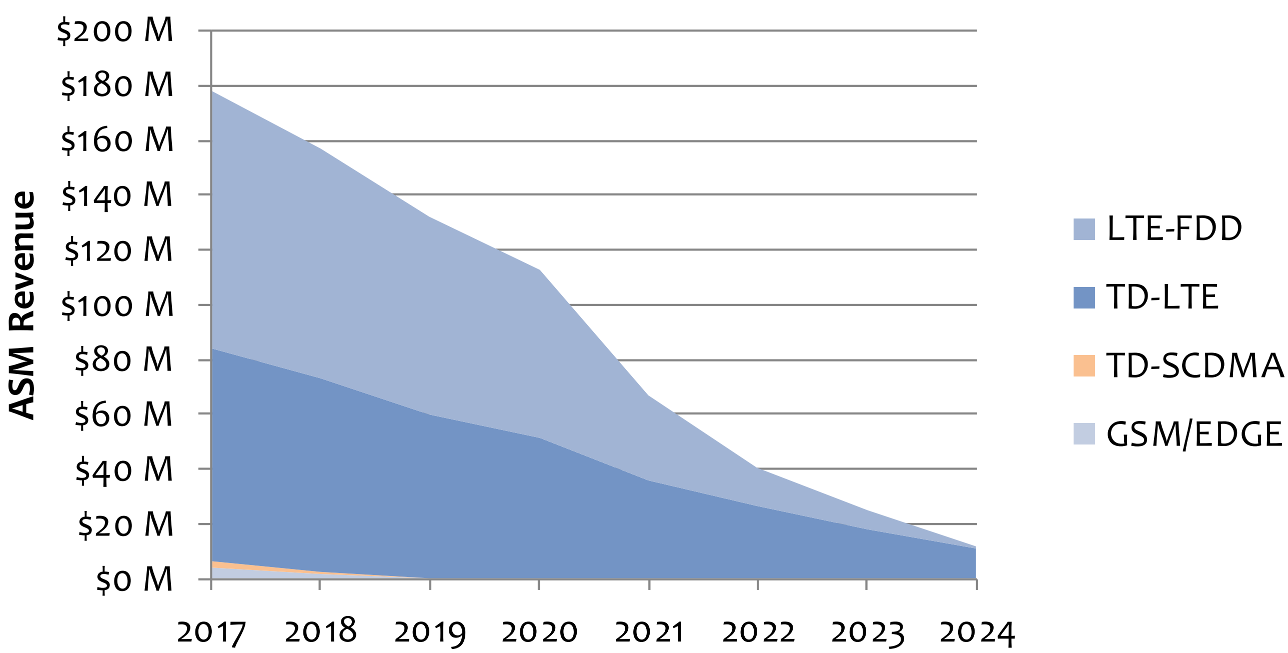


Chart 63: ASM Revenue, by air interface, 2018-2024

Source: Mobile Experts

Tx Module Outlook

Transmit modules (defined as PA and antenna switch) are the default approach to the transmitter function for GSM/3G, in basic phones and many smartphones as well. The trend has been downward as more CFE- and MMPA-based architectures are used, but we're forecasting that TxM units will level off at about 250-300 million per year as this may continue to be the simplest, cheapest, easiest way to include a single-band RF front end.

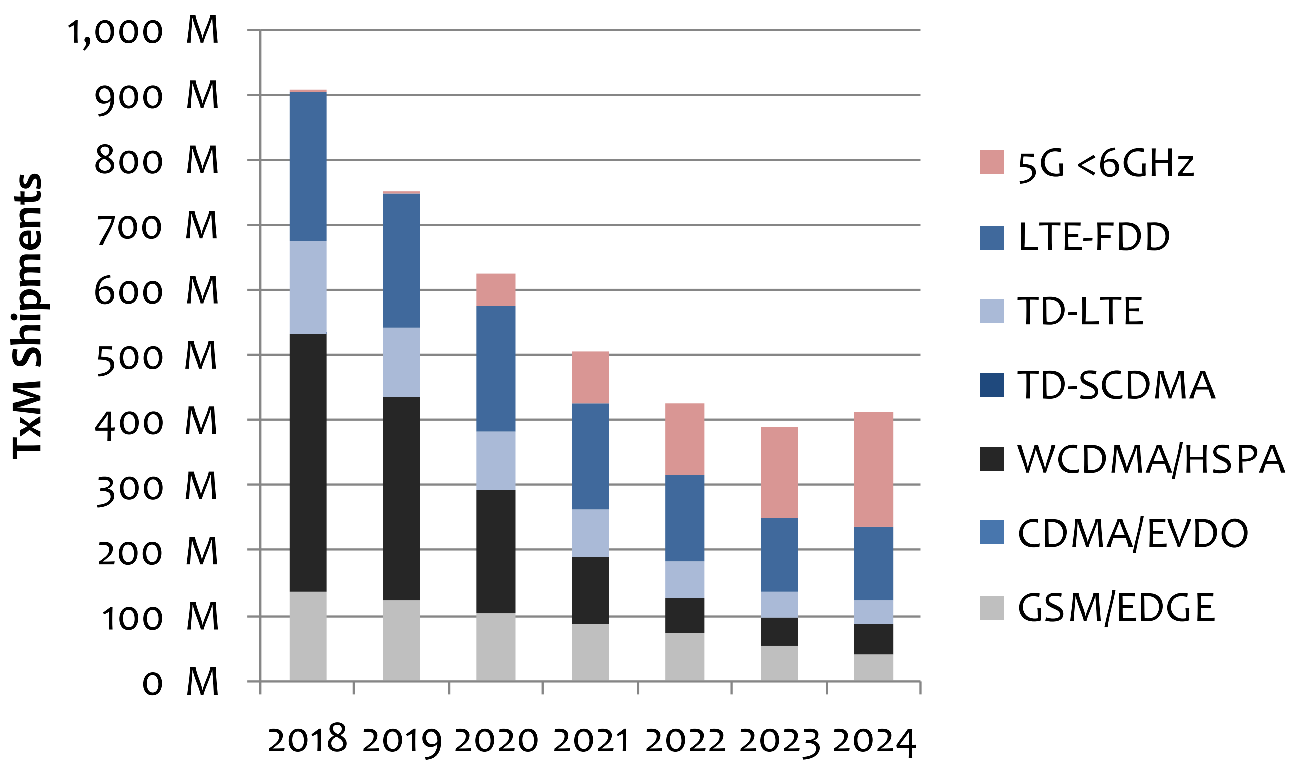


Chart 64: TxM Shipments, by air interface, 2018-2024

Source: Mobile Experts

Low-cost Chinese companies have taken a significant share of the TxM market, and have most certainly driven price erosion for Skyworks and Qorvo in the pockets that they continue to support.

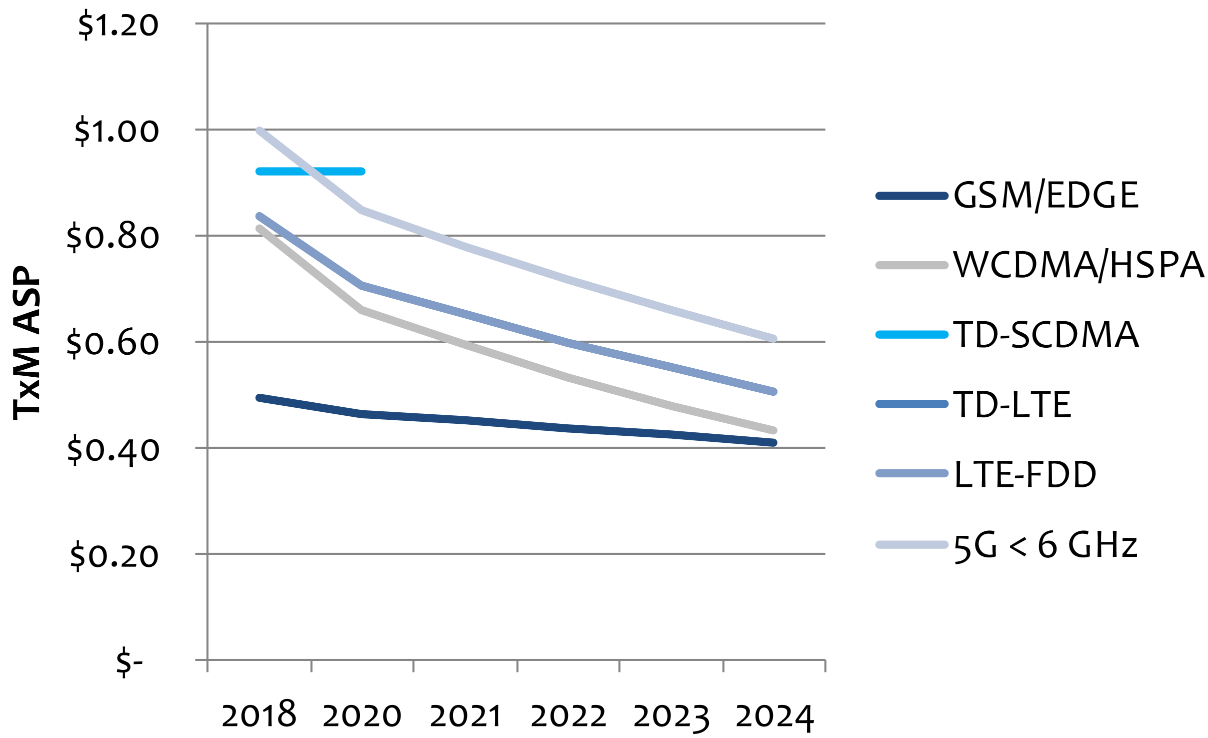


Chart 65: TxM ASP, by air interface, 2018-2024

Source: Mobile Experts

We can think of TxM modules almost as discrete devices, and as 5G is introduced, any low-tier handset that includes a single 5G band may be a candidate for a TxM with a simple bandpass filter to achieve 5G coverage for less than a dollar.

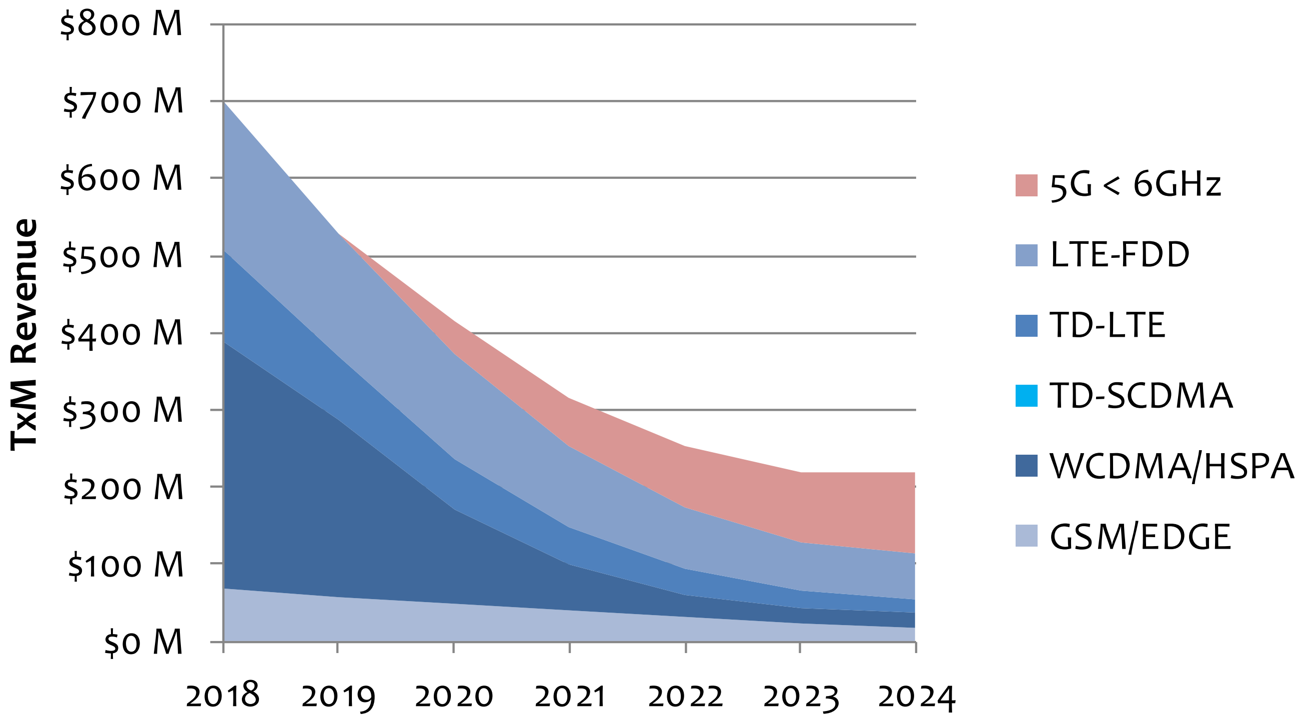


Chart 66: TxM Revenue, by air interface, 2018-2024

Source: Mobile Experts

MMPA Outlook

In many smartphones, the TxM covers the GSM mode and a combination of switched duplexers and MMPAs covers the 3G/4G capability. This flexible and inexpensive combination constitutes a large percentage of the market, with a lot of Chinese smartphone brands following the Mediatek "Phase 2/Phase 3" architecture (whether Mediatek is actually used as the modem or not). Multimode Multiband Power Amplifiers (defined as a PA covering multiple RF states plus a band switch) are a good way to handle multiple 3G and 4G bands with flexibility on the waveform and peak-to-average ratio of the signal.

5G will also become a part of this product type, as 5G is deployed in the existing LTE bands, and to some extent in the 2.5 through 4.9 GHz bands.

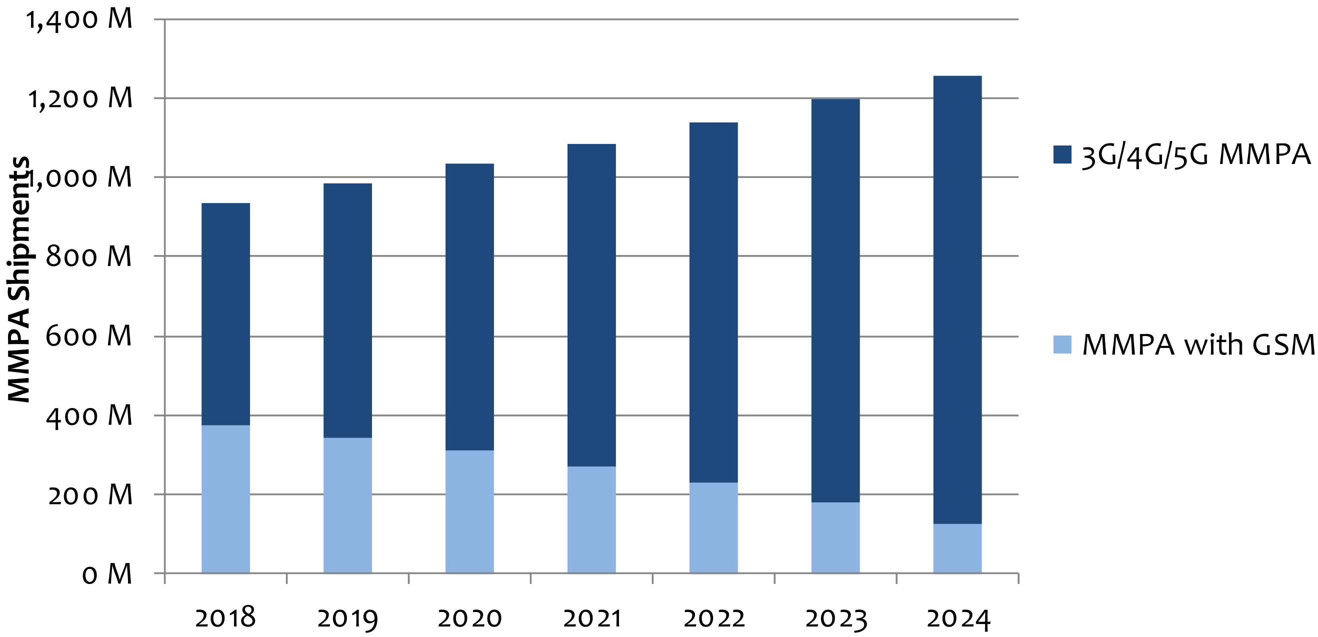


Chart 67: MMPA Shipments, with and without GSM path, 2018-2024

Source: Mobile Experts

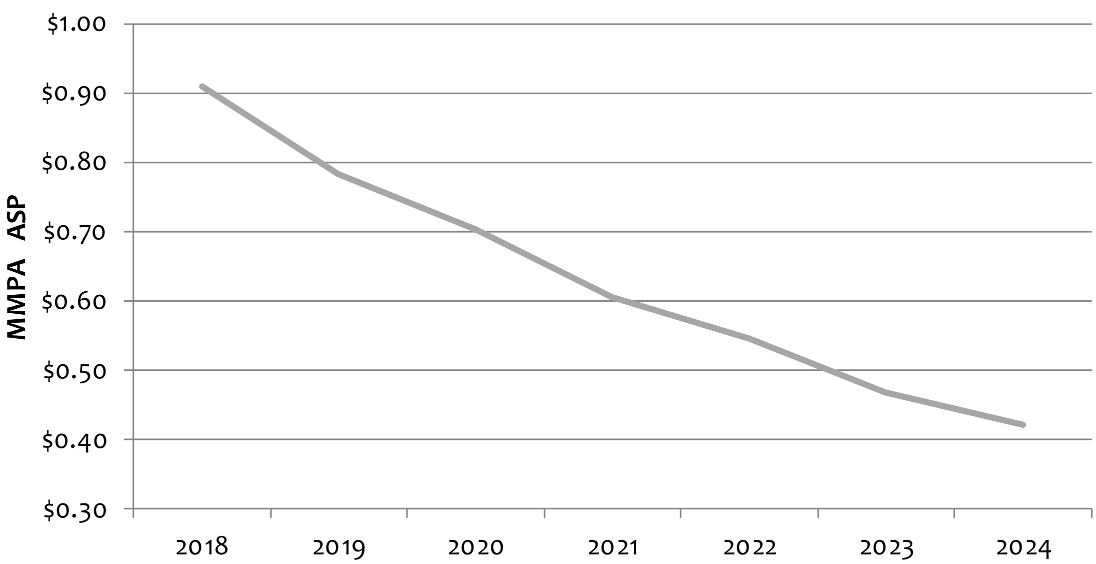


Chart 68: MMPA Average Pricing, 2018-2024

Source: Mobile Experts

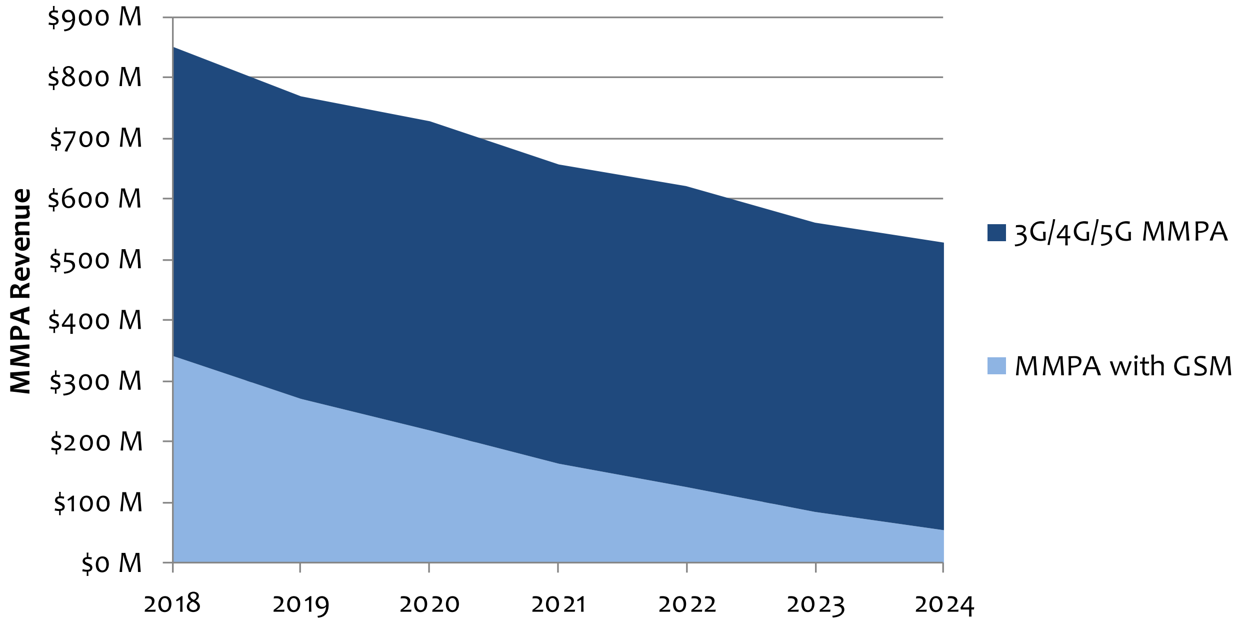


Chart 69: MMPA Revenue, With and without GSM, 2018-2024

Source: Mobile Experts

Switched Duplexer Bank (aka FEMiD) Outlook

The Switched Duplexer Bank is the counterpart to the MMPA, but the dynamics are a bit different because the MMPA unit volume doesn't grow along with new bands, and the switched duplexer bank takes on more content as new bands are added. We see some growth with the low-end smartphones adding more SDBs for low and high bands, but after about 2020 we expect this market to decline gradually, along a similar track as the MMPA.

Also, the content in the SDBs will change as the market migrates from 4-5 bands per module to somewhere between 6 and 10 bands per module.

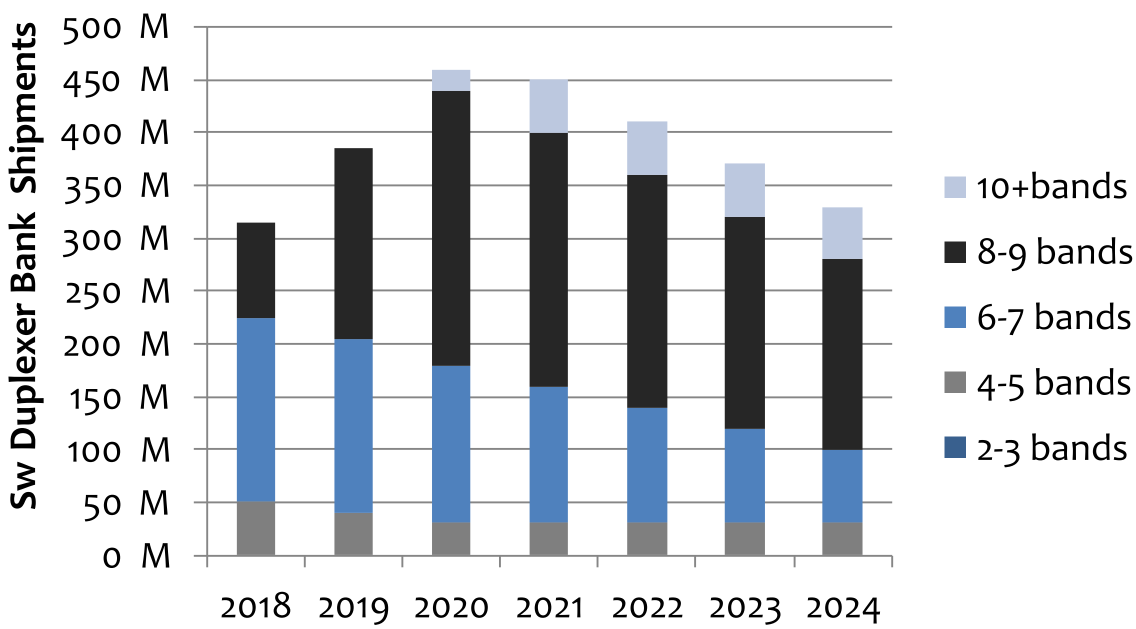


Chart 70: Switched Duplexer Bank Shipments, by number of bands, 2018-2024

Source: Mobile Experts

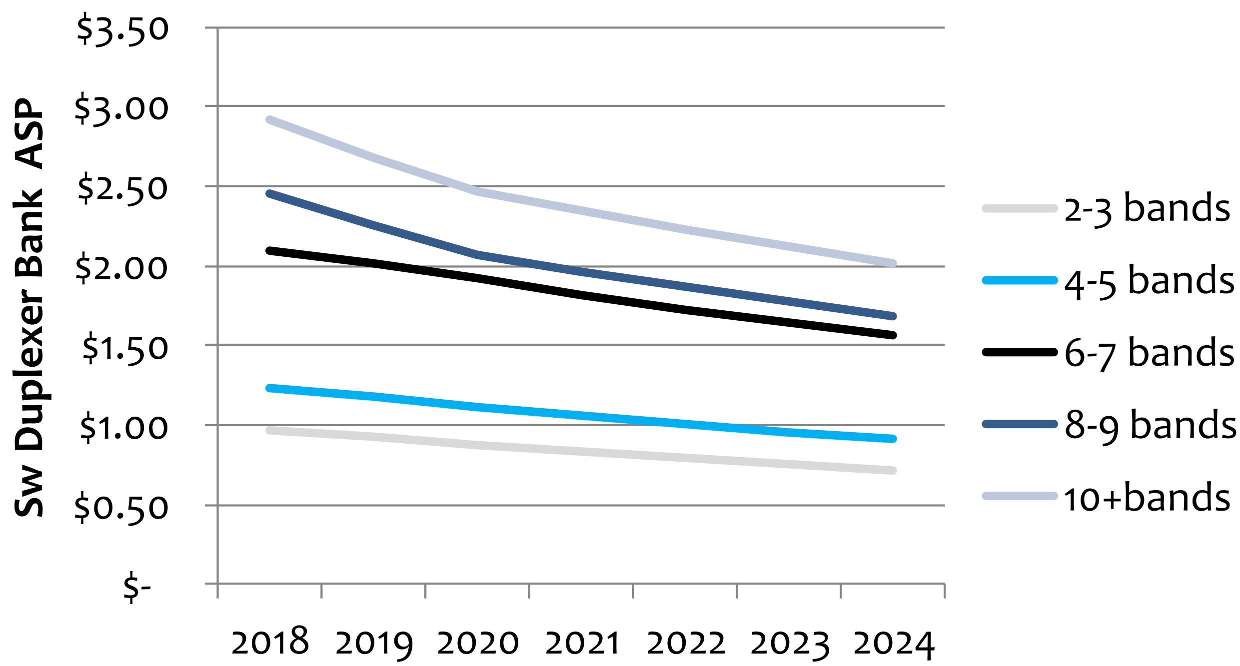


Chart 71: Switched Duplexer Bank ASP, by number of bands, 2018-2024

Source: Mobile Experts

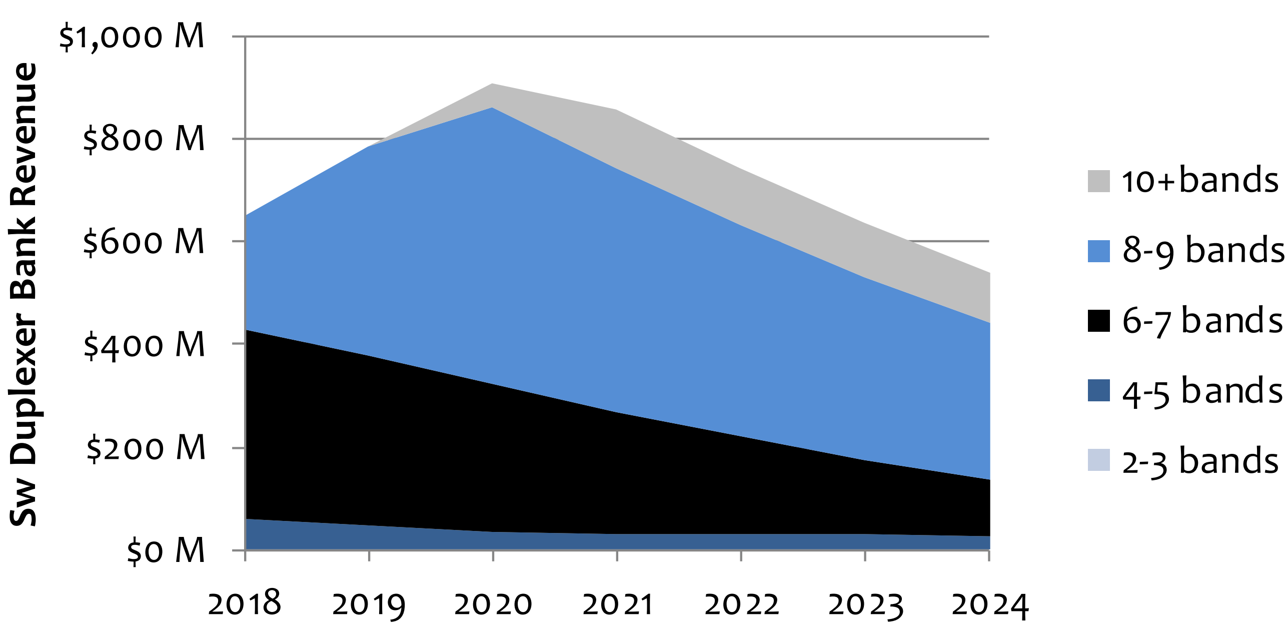


Chart 72: Switched Duplexer Bank Revenue, by number of bands, 2018-2024

Source: Mobile Experts

Diversity Module Outlook

Diversity modules are still growing nicely, as hundreds of millions of phones are converting from 2x2 MIMO to 4x4 MIMO and volume is added. 5G will also add volume or numbers of bands to this segment. Diversity modules are dominated by tight integration and low cost, and the level of functionality is growing quickly. The tight integration leads to a pricing premium which makes this segment very attractive for filter vendors.

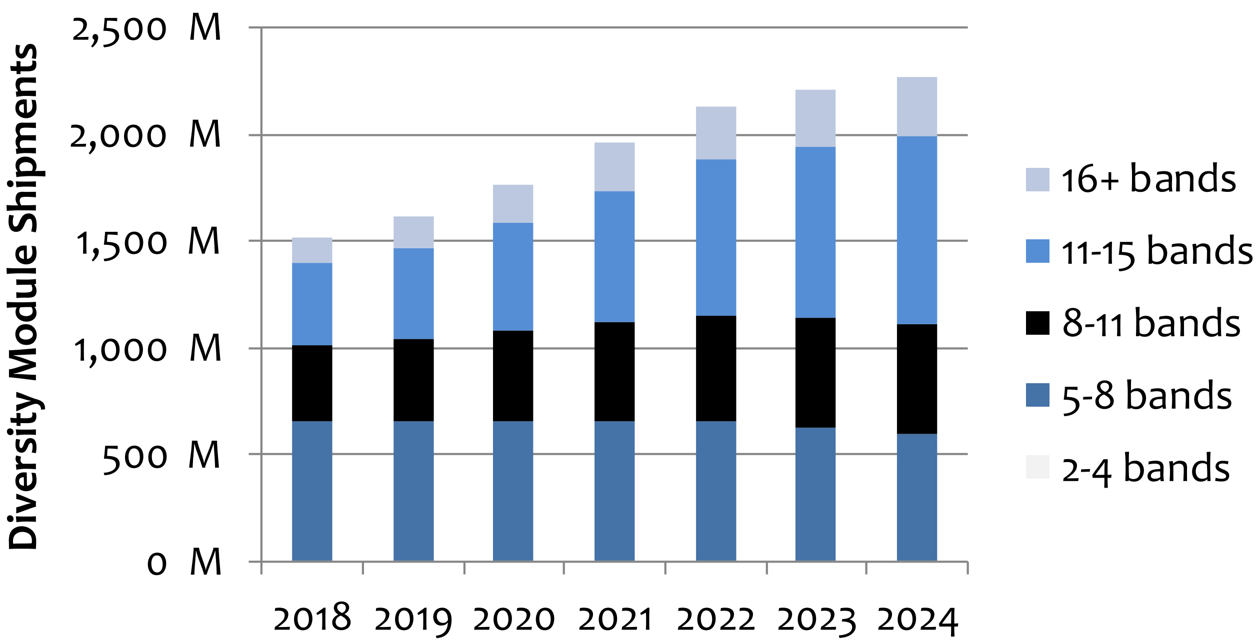


Chart 73: Diversity Filter Bank Shipments, by number of bands, 2018-2024

Source: Mobile Experts

Pricing depends mainly on the number of bands included. Of course, higher numbers of bands in a small size can drive a boost in pricing as well. We are seeing strong price competition, which is driving down the ASP for high-band-count DxM's, to the point that the ASP erosion offsets the volume growth.

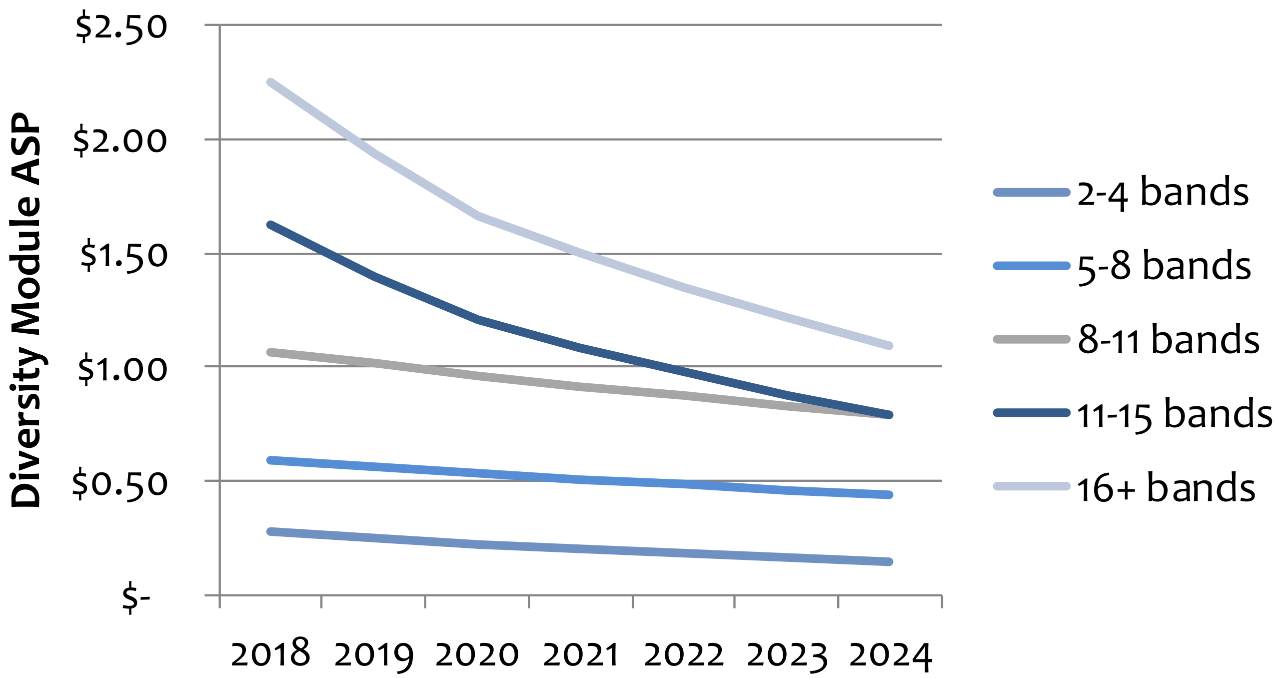


Chart 74: Diversity Filter Bank ASP, by number of bands, 2018-2024

Source: Mobile Experts

One small downside here is that Uplink MIMO will be reducing the numbers of Diversity Modules, as a DRx would be replaced by a CFE in some cases. Downlink MIMO growth will be more impactful than UL MIMO growth, so this is not a major concern. More significantly, the price erosion flattens out the revenue picture, even for an important function like the Diversity Module.

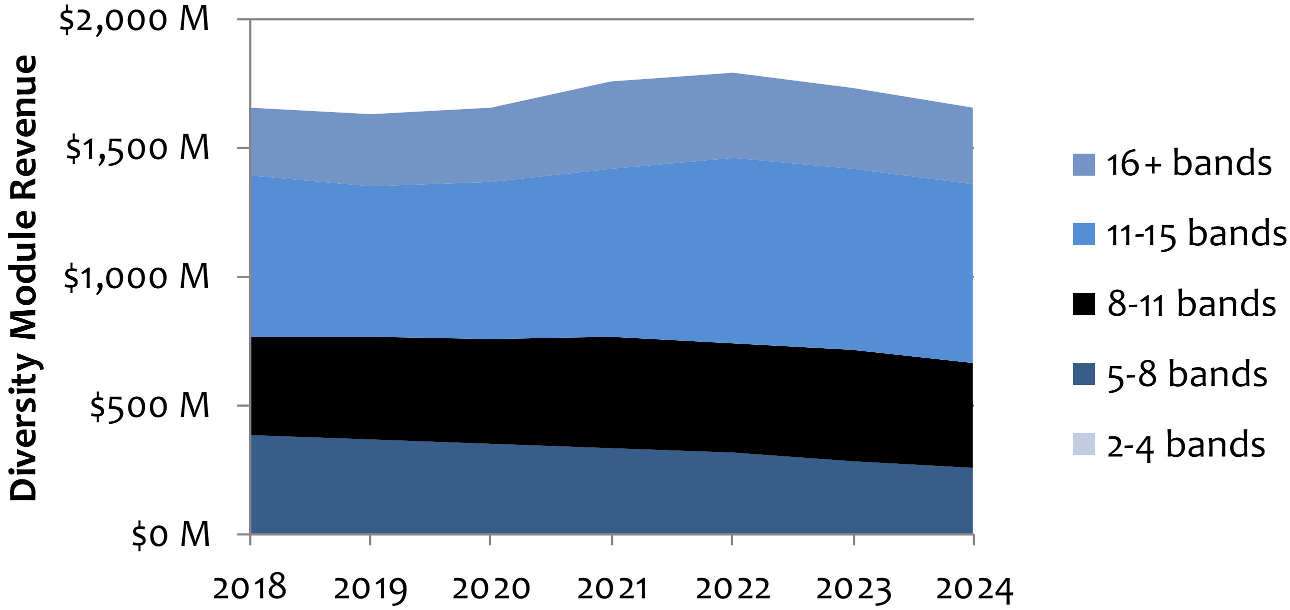


Chart 75: Diversity Filter Bank Revenue, by number of bands, 2018-2024

Source: Mobile Experts

Complete Front End (CFE) Outlook (including PAMiD, LPAMiD and LPAF)

The Complete Front End contains all of the RF functions (LNA, filter, switch, PA) that are specific to each band. These are generally used in band groups, as very few of these CFEs are sold to cover ALL of the frequency bands in a handset.

CFEs are generally segmented by the group of bands covered:

- Ultra-low bands include 600-700 MHz
- Low bands generally refer to 800, 850 and 900 MHz
- Mid bands range from 1700 MHz to 2100 MHz
- Hi bands cover the 2100-2700 MHz range
- Ultra-hi bands range from 3300 to 4990 MHz

There's a lot of crossover between the mid-bands and high bands, because one primary reason for using CFEs is to limit the number of components. In fact, the standard configuration nowadays is to use a combination mid-hi band CFE to incorporate all bands in the 1700 to 2600 MHz range.

The level of complexity gets more difficult as mid-high combinations are used, or as two bands within the same band grouping are used in Carrier Aggregation. In the case that two bands are used in the same CFE, switches cannot be used to select the filter components. Instead, multiplexers (quadplexers, hexaplexers, and others) are used for simultaneous operation.

The new 5G bands at 3.5 GHz to 4.9 GHz (n77, n78, n79) will involve LPAF components (Low Noise Amplifier, Power Amplifier, Band-pass Filter) and initially may be implemented with only one or two 5G bands per handset. Over time we may see these incorporated with the mid-hi band CFE but for now they are designed as separate modules.

One of the growth drivers for the CFE market will be Uplink MIMO. To the extent that two PA-based components are needed instead of one for TD-LTE or 5G handsets, we will see higher quantity of these modules sold. If the volume justifies it, the OEMs will ask for customization of the secondary UL MIMO module, to incorporate only the PA bands that utilize uplink MIMO.

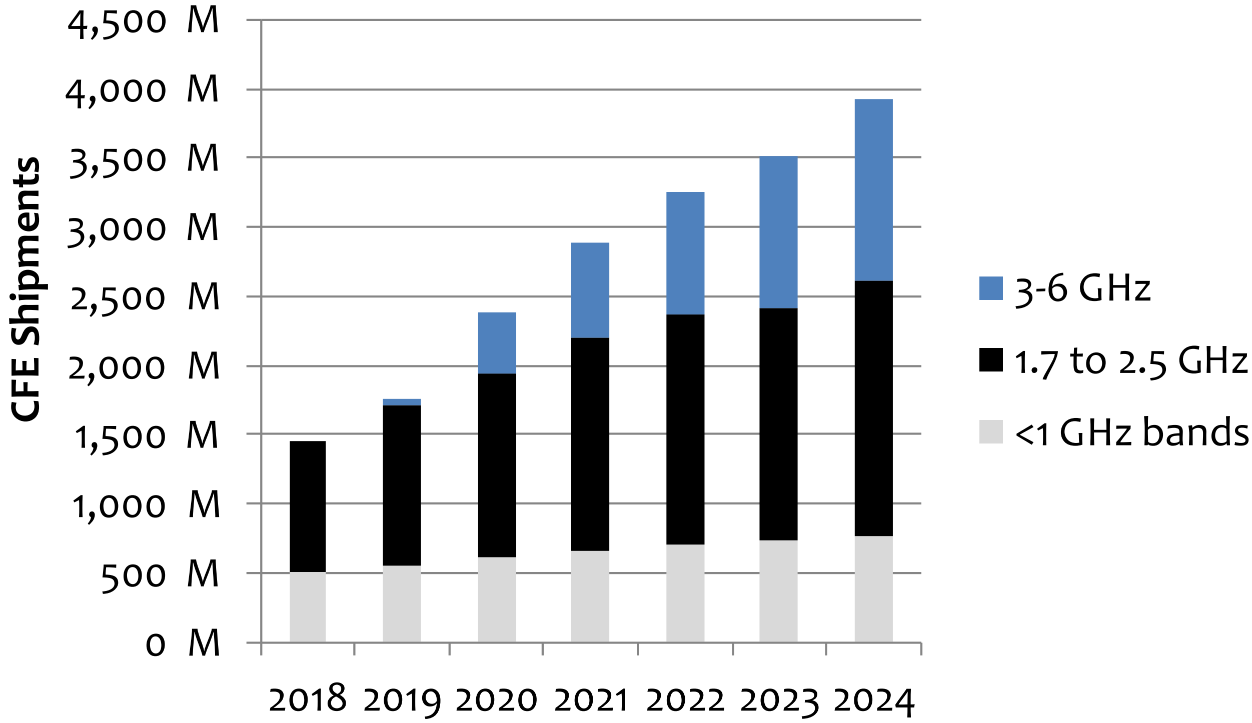


Chart 76: CFE Shipments, by primary frequency block, 2018-2024

Source: Mobile Experts

Pricing for CFEs is eroding this year, as we have a lot of competition between Broadcom, Qorvo, Skyworks, Qualcomm, and in some cases Murata. There are some areas that are more protected, such as CFEs including hexaplexers or other difficult functions. In particular, the new bands in the 3-5 GHz range are likely to start with some higher pricing due to the wide bandwidth of the PA involved… and this factor may limit competition which could result in less pressure in the upper bands. However, over time we expect that filter solutions will find their way to all of the vendors.

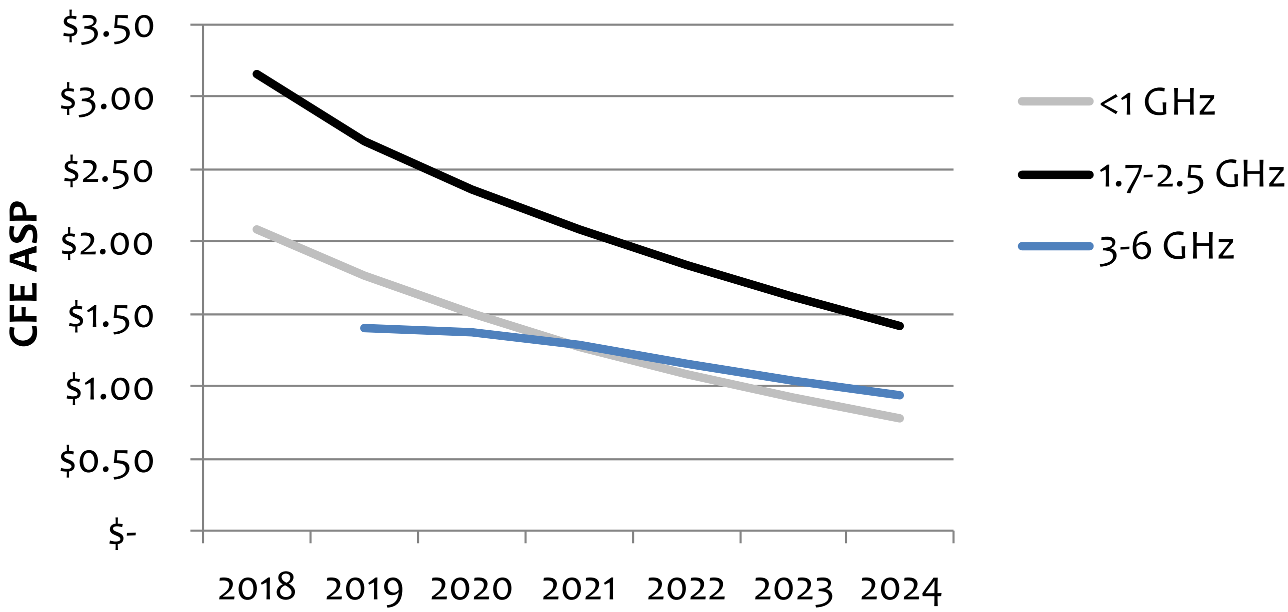


Chart 77: CFE ASP, by number of bands, 2018-2024

Source: Mobile Experts

Growth is strong for CFEs as more handset vendors take advantage of higher levels of integration, and the band count continues to grow.

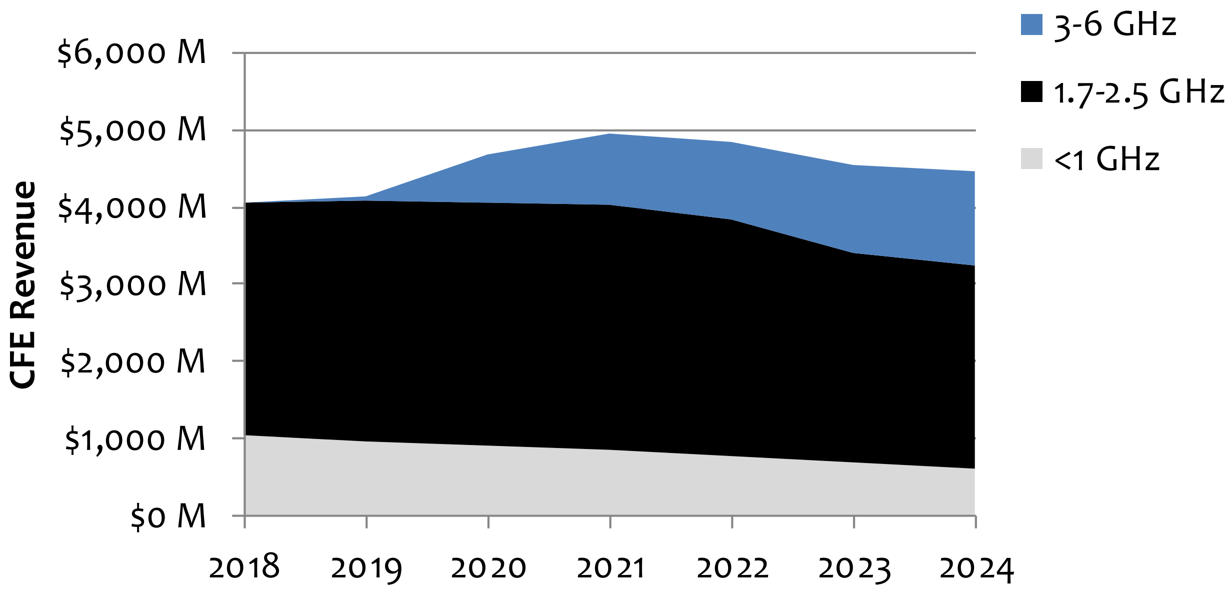


Chart 78: CFE Revenue, by band grouping, 2018-2024

Source: Mobile Experts

Overall Power Amplifier Outlook

The PA market has not grown in a long time, because MMPAs have gradually replaced PAs for individual bands, effectively reducing the content devoted to the PA function. For this reason, the PA has transitioned from the 'most important' component in the RFFE to a more minor component, based on dollar value. MIMO and CA have not impacted the number of PAs so far, because almost all phones have been based on a single transmitter. That will change with small numbers of Uplink MIMO handsets, which will drive new PA content.

There are some upcoming features that may be able to drive a little growth for PAs, or at least enough growth to offset ongoing price erosion:

- 5G NR is now in handsets, in the 3.5 and 4.5 GHz ranges. The wide bandwidth of the 5G channel will require high performance for the PA, and opens some interesting areas of differentiation for ET and module integration.
- Along with 5G NR, we should see the introduction of uplink 2xn MIMO. China Mobile has made this a requirement for their 5G plans, but we're waiting to see how many phones really use this feature.

- Uplink carrier aggregation is also an option, although we expect that this will not impact the number or pricing of PAs because lo-hi combinations are likely to be used, so that existing PAs can satisfy the requirement.

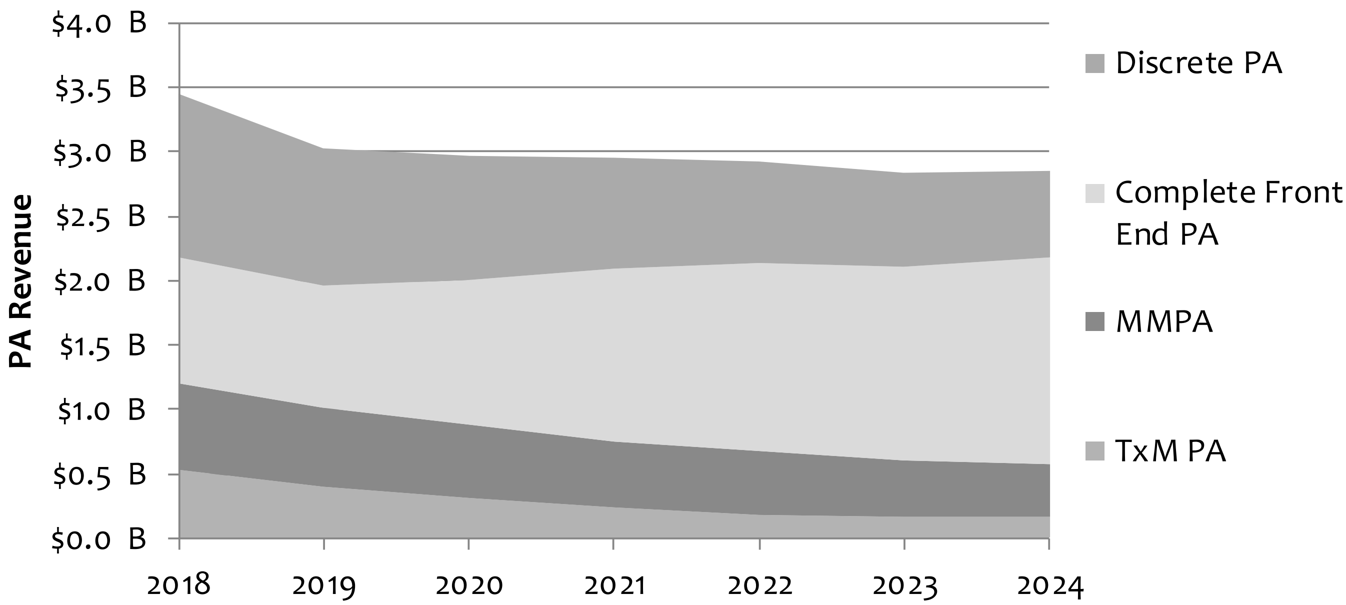


Chart 79: Overall PA Revenue, by PA contribution to various modules, 2018-2024

Source: Mobile Experts

Discrete Power Amplifier Outlook

Discrete power amplifiers are flexible for multiple applications where an additional band is needed, or uplink MIMO is desired, or for terminals with low numbers of bands (such as IoT devices).

One possible upside to the current forecast may emerge with uplink MIMO and uplink Carrier Aggregation. It's not clear whether the OEMs will use a second CFE (to handle the diversity receiver filter needs and the PA) or whether they'd implement a DRx and a discrete PA. We believe that some discrete PAs will be used in these cases because only a few bands will use uplink MIMO.

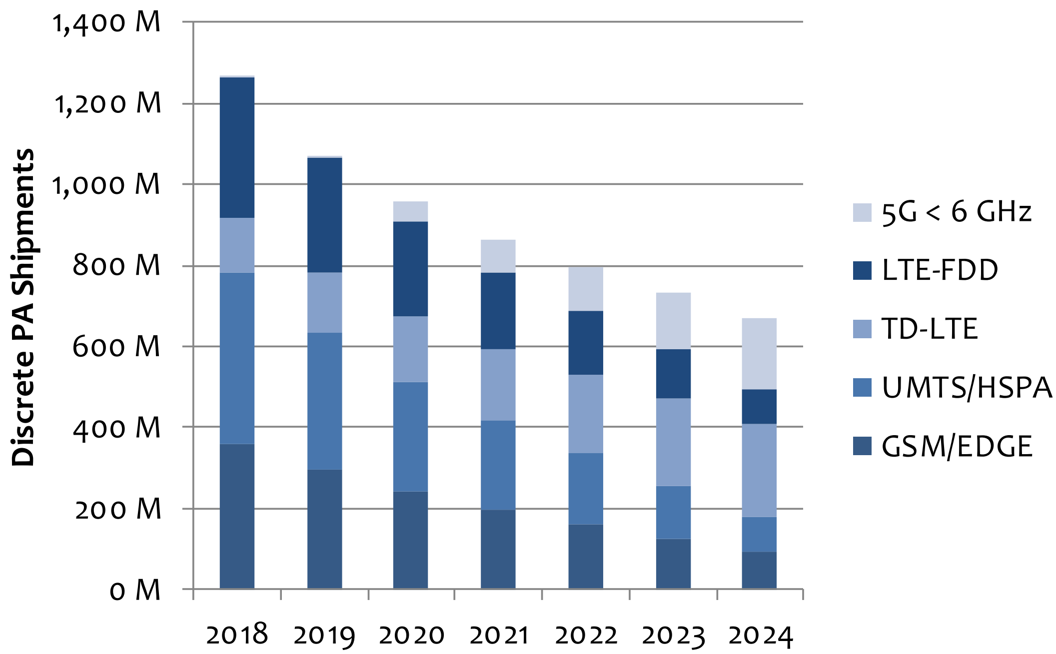


Chart 80: Discrete PA Shipments, by air interface, 2018-2024

Source: Mobile Experts

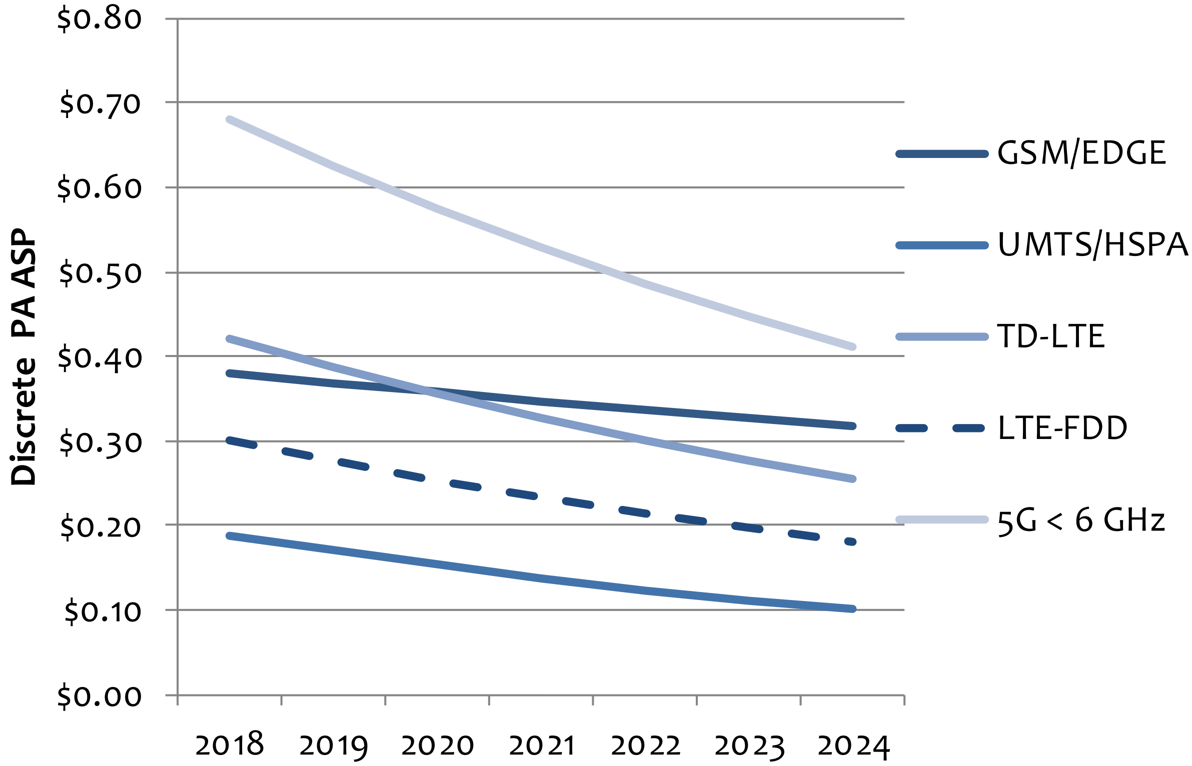


Chart 81: Discrete PA ASP, by air interface, 2018-2024

Source: Mobile Experts

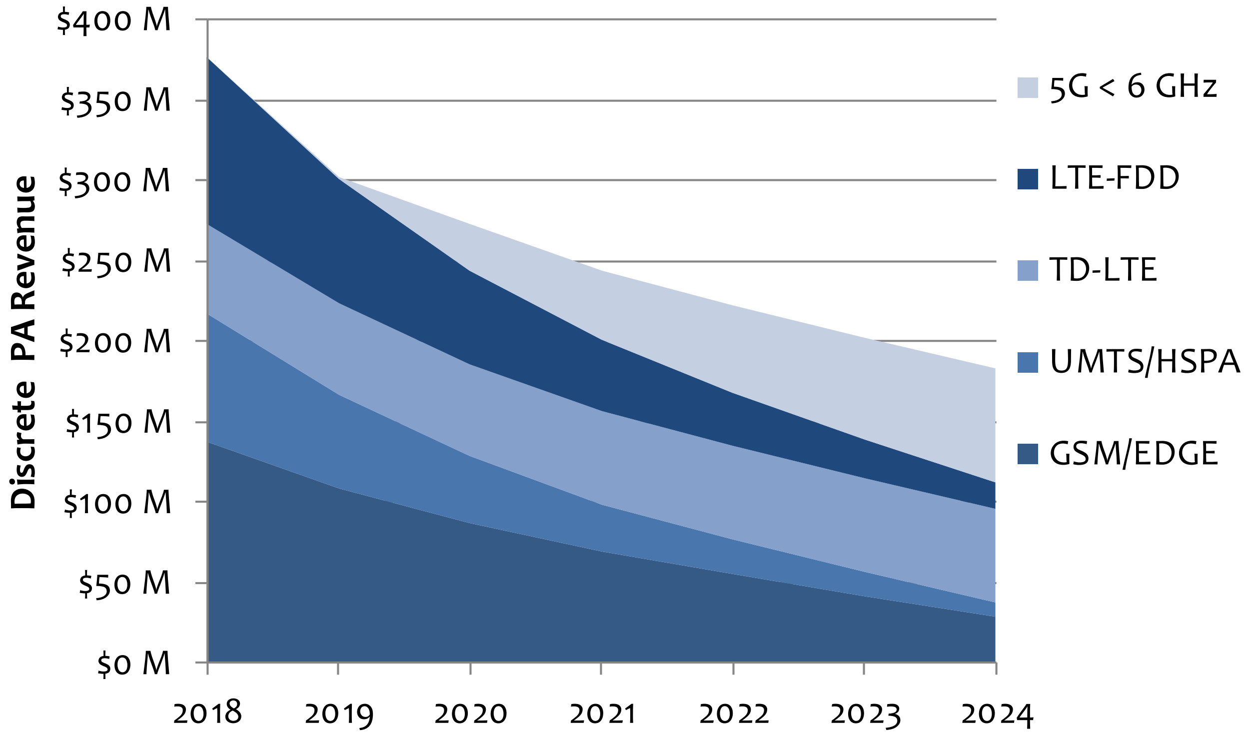


Chart 82: Discrete PA Revenue, by air interface, 2018-2024

Source: Mobile Experts

Envelope Tracking Power Amplifier Outlook

Top-tier handset OEMs went through a lot of pain to develop ET, and it has become a standard feature in the premium market. The shift to 5G and wideband channels will make ET difficult again. We don't think that the major vendors want to take a backward step on battery life, so they will engage again on the difficult work to make ET perform.

Note that Mobile Experts does not attempt to forecast the revenue for Envelope Tracking Power Supplies. Despite the high speed nature of the power supply, we don't consider the power supply to be an "RF" device. As companies like Qualcomm start to provide the ET power supply and the amplifier, this may get messy as the ET modulator could be integrated with the CFE or PA module.

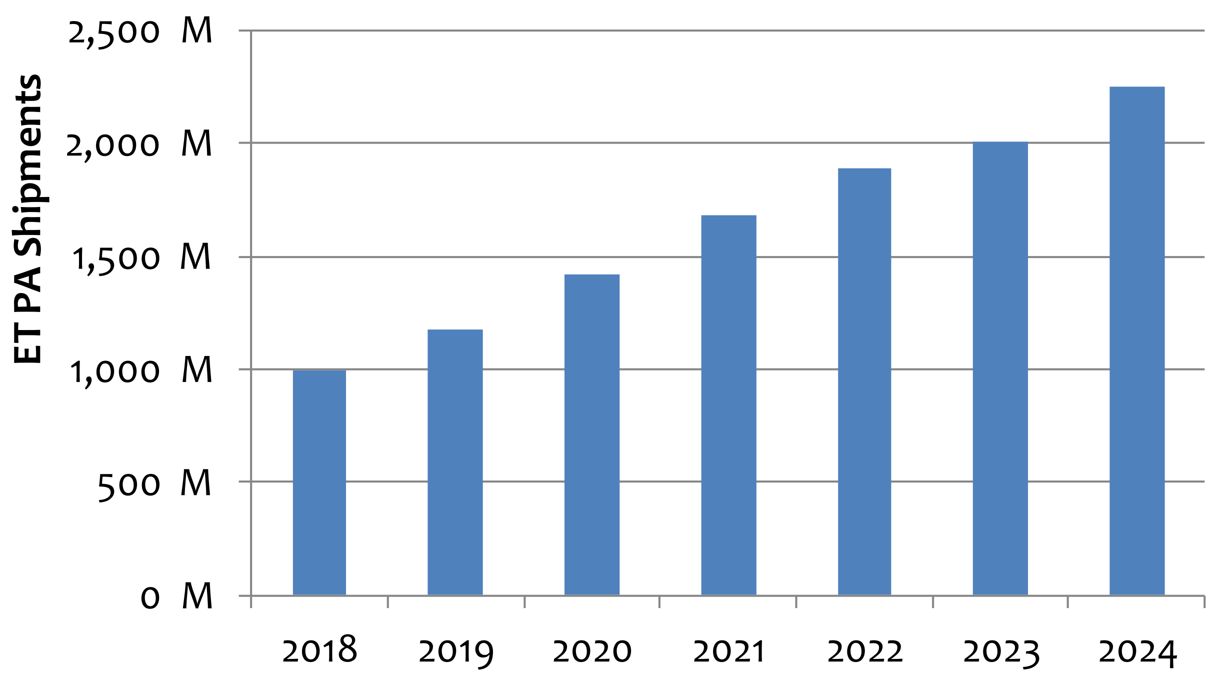


Chart 83: ET PA Shipments, 2018-2024

Source: Mobile Experts

We aren't tracking any price differences between ET power amplifiers and amplifiers that use APT (Average Power Tracking) power supplies. There may be a cost difference, but these PA products are generally embedded in CFE products today, so we can't determine whether the ET feature makes a difference at a pricing level.

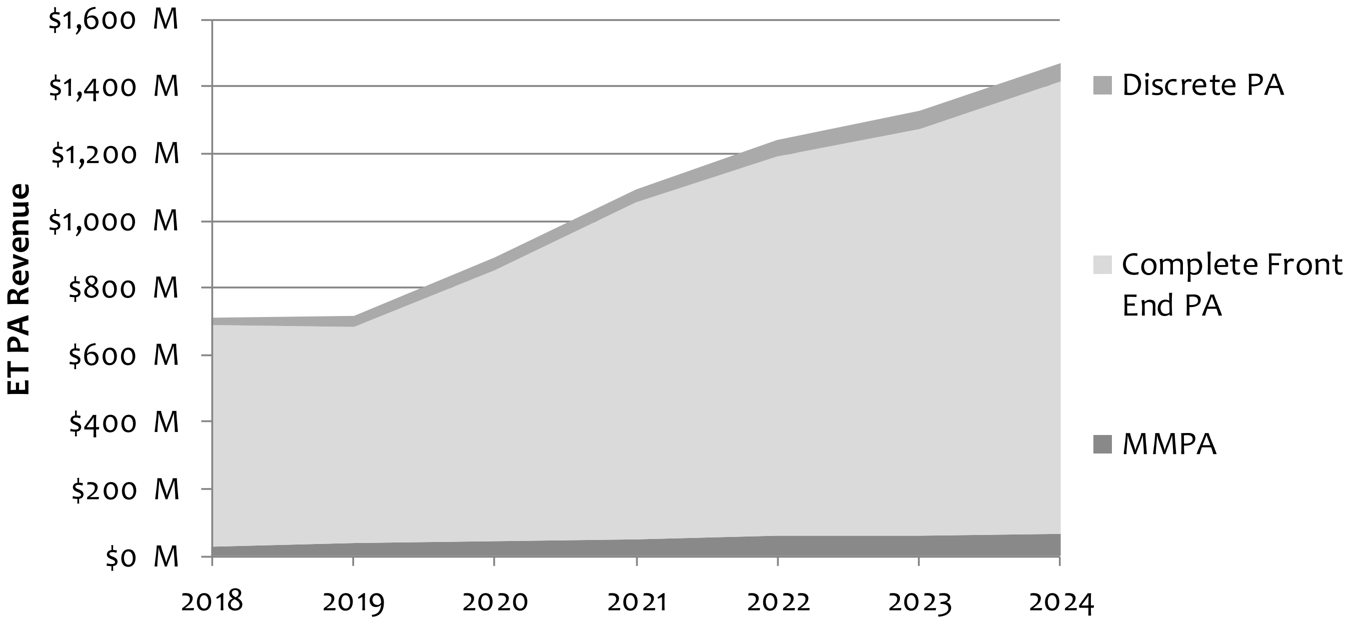


Chart 84: ET PA Revenue, by module type, 2018-2024

Source: Mobile Experts

Summary: Overall Filter Outlook

All kinds of filters are used in the RF Front End section of a mobile terminal. Roughly half of the filters sold are part of multi-function modules. Another 15% of filter die are integrated into multiplexers, antennaplexers, and other multiband combinations. The remaining discrete filter products are generally bandpass filters and duplexers.

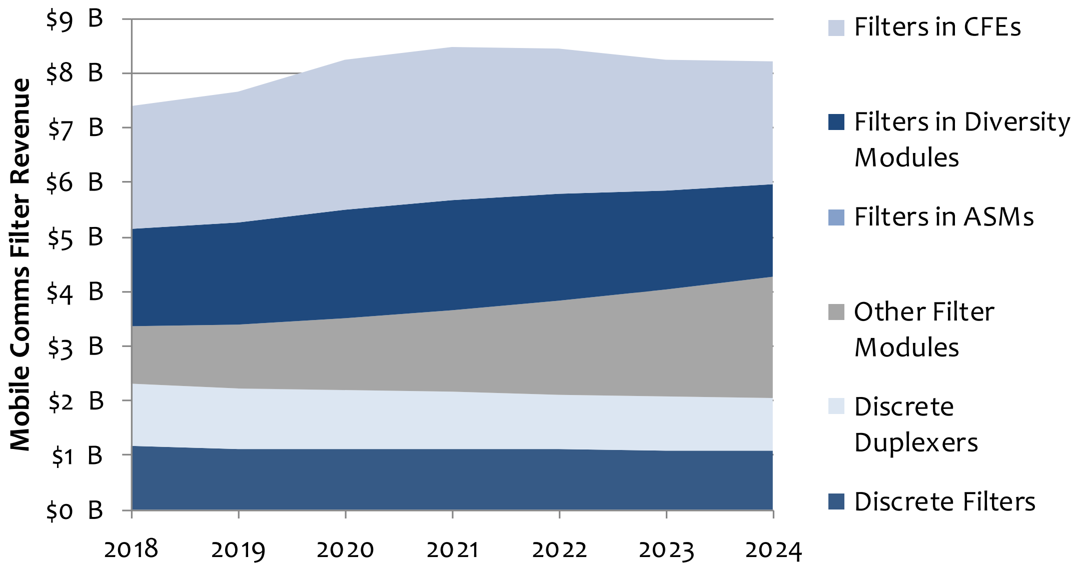


Chart 85: Overall Filter Revenue, by module type, 2018-2024

Source: Mobile Experts

Filter technology is also changing. New ideas such as thin-film SAW and single-crystal BAW filters are coming to market, offering new ways to hit high performance targets. TC-SAW continues to encroach on "BAW Territory", but we continue to see new filter requirements that stretch the capabilities of the best FBAR filters.

We should also mention that in the 3.5 to 4.5 GHz bands, ceramic filters have been perceived as an alternative… although other options are coming along that will perform better in a smaller size.

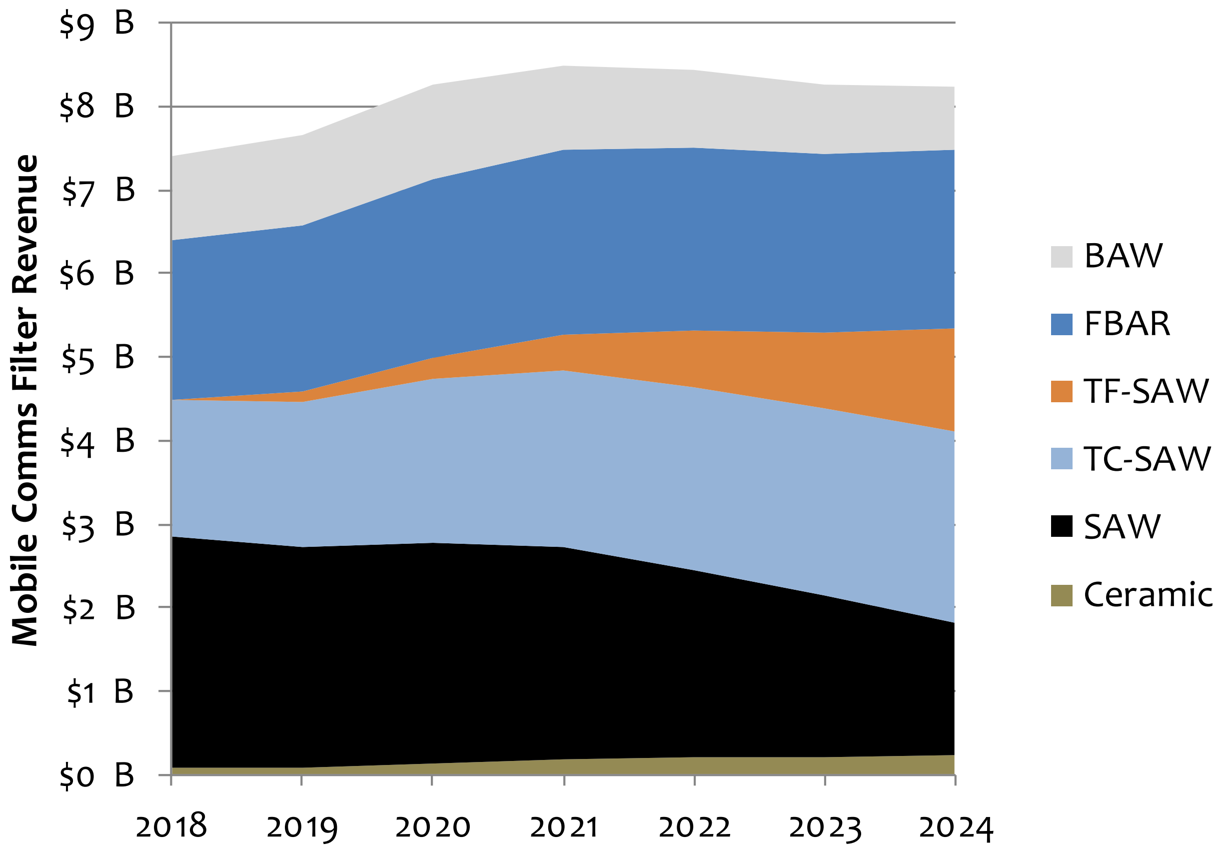


Chart 86: Overall Filter Revenue, by process technology, 2018-2024

Source: Mobile Experts

The growth rate is much more apparent in looking at expected shipments of filter die. Also, in the following chart it's clear that FBAR and BAW filters carry a higher price per unit than SAW devices.

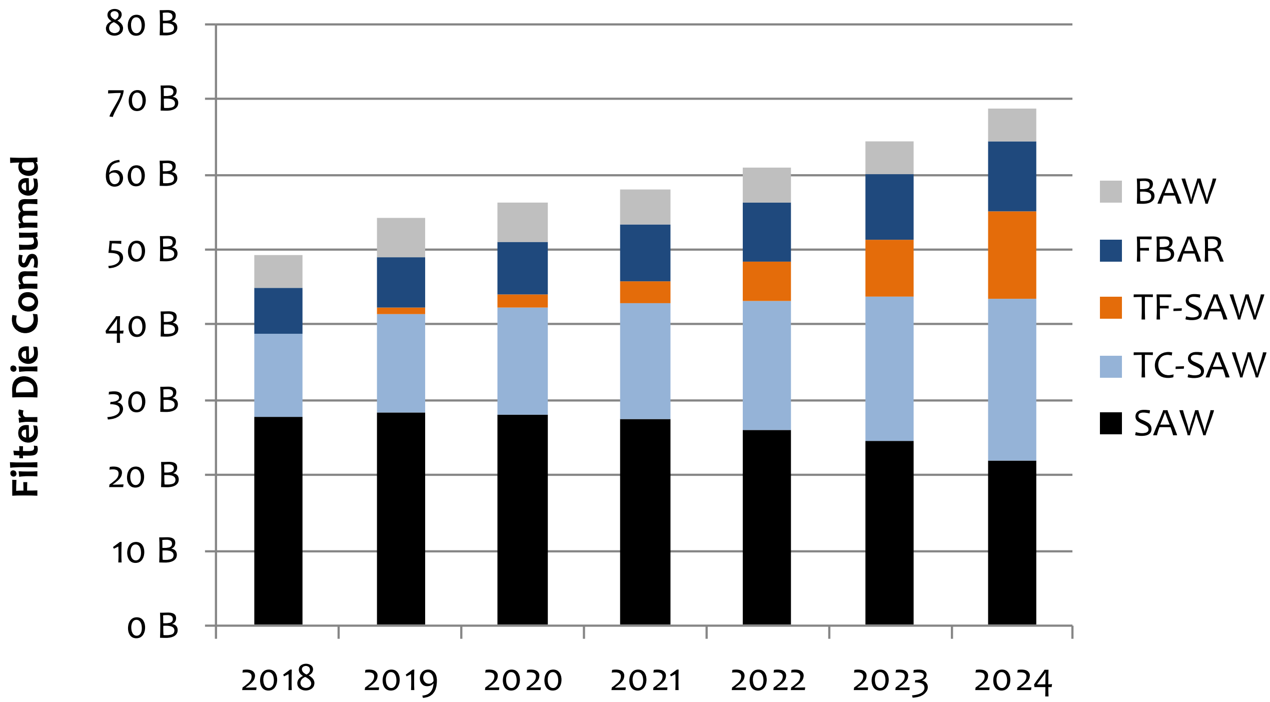


Chart 87: Number of Filter Die Used, by process technology, 2018-2024

Source: Mobile Experts

Discrete Bandpass Filter Outlook

TDD modes and MIMO receivers drive strong demand in the number of simple band-pass filters used in smartphones. Most BPFs use SAW and TC-SAW technology. Also, a few inter-stage filters still exist despite the best efforts of OEMs and module designers to eliminate them.

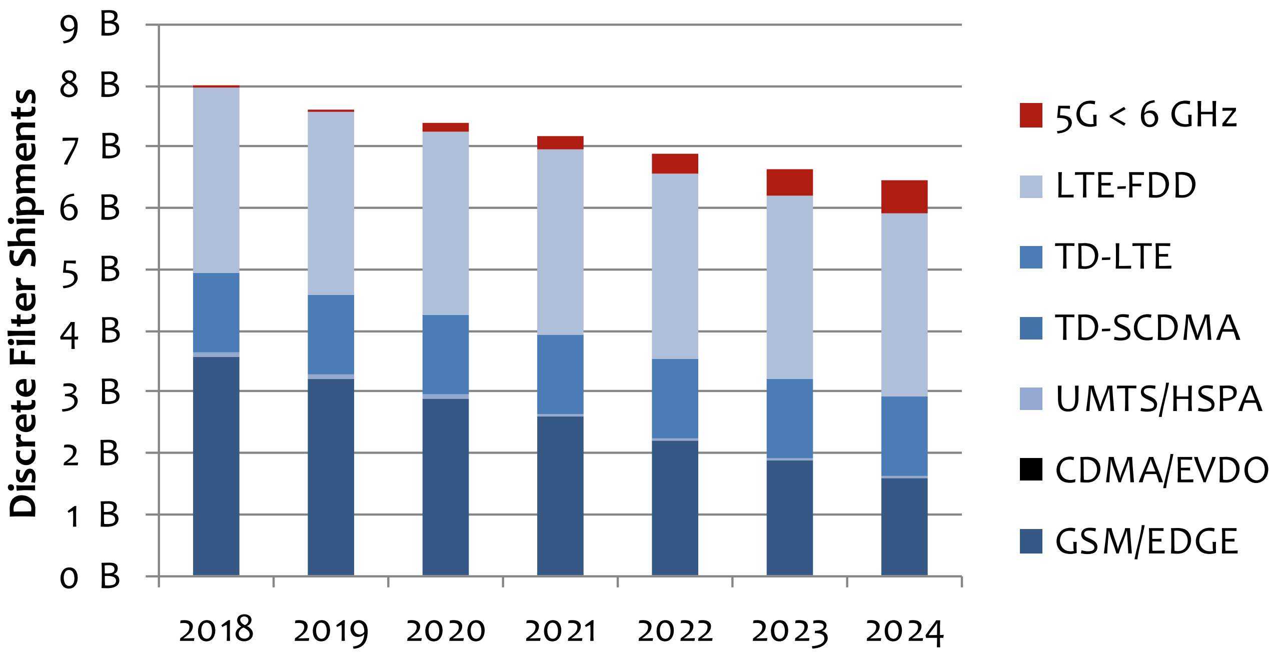


Chart 88: Discrete Bandpass Filter (BPF) Shipments, by air interface, 2018-2024

Source: Mobile Experts

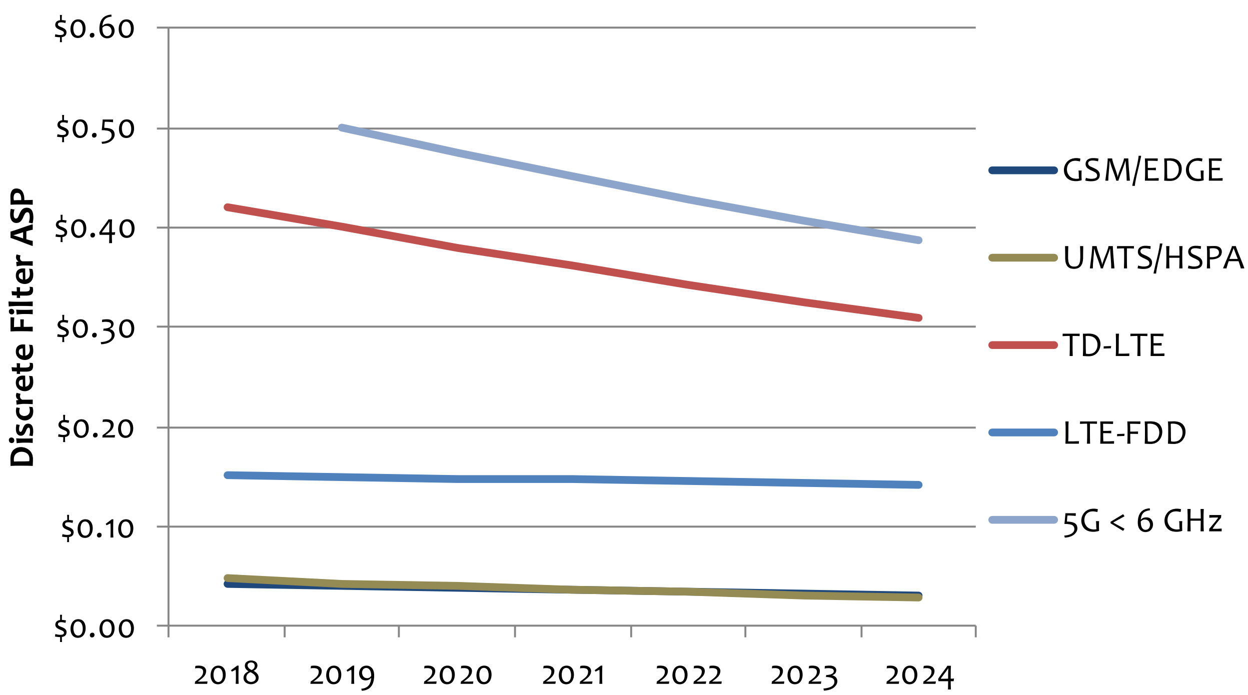


Chart 89: Discrete BPF ASP, by air interface, 2018-2024

Source: Mobile Experts

New 5G bands will sell for a higher price, especially filters with wide bandwidth and good WI-Fi coexistence performance. Overall price erosion will be steady, but possibly lighter in the wideband/Wi-Fi coexistence market where even the BAW vendors may not be able to meet requirements.

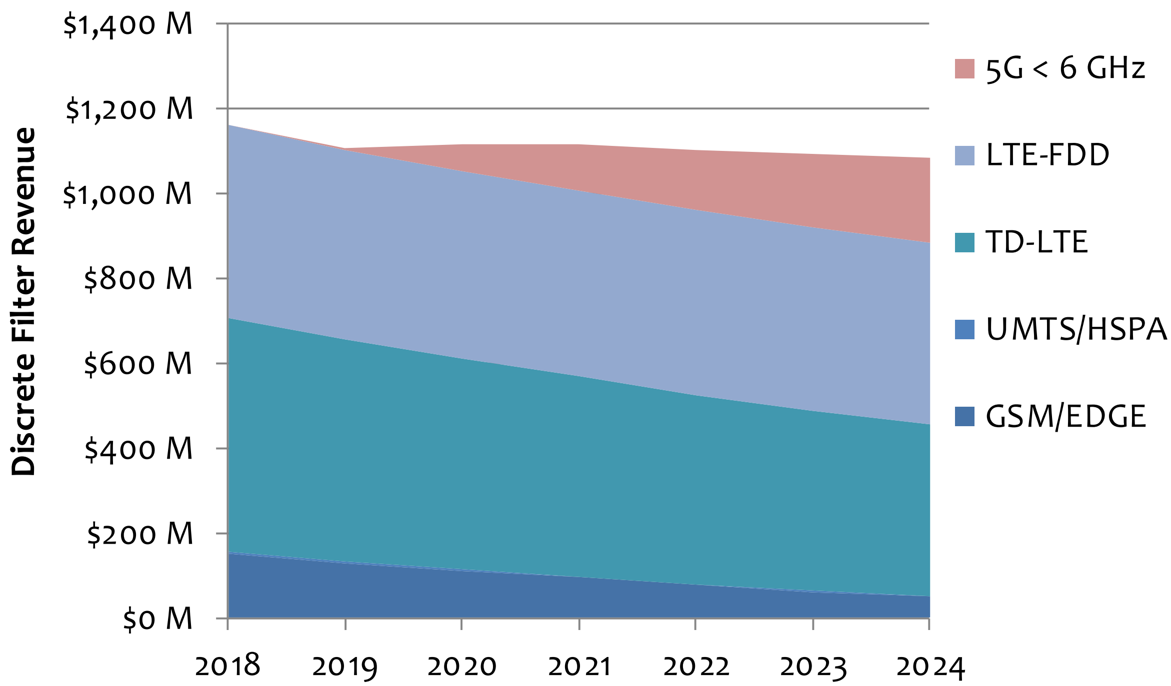


Chart 90: Discrete BPF Revenue, by air interface, 2018-2024

Source: Mobile Experts

Overall discrete filter revenue will be held up by the new wideband 5G filters, as discrete solutions take a role in supporting 5G Tx Modules at relatively high prices. In general, BPFs will never disappear because odd combinations of frequency bands will require a few discretes at times, and some low-end radios use discrete devices rather than modules.

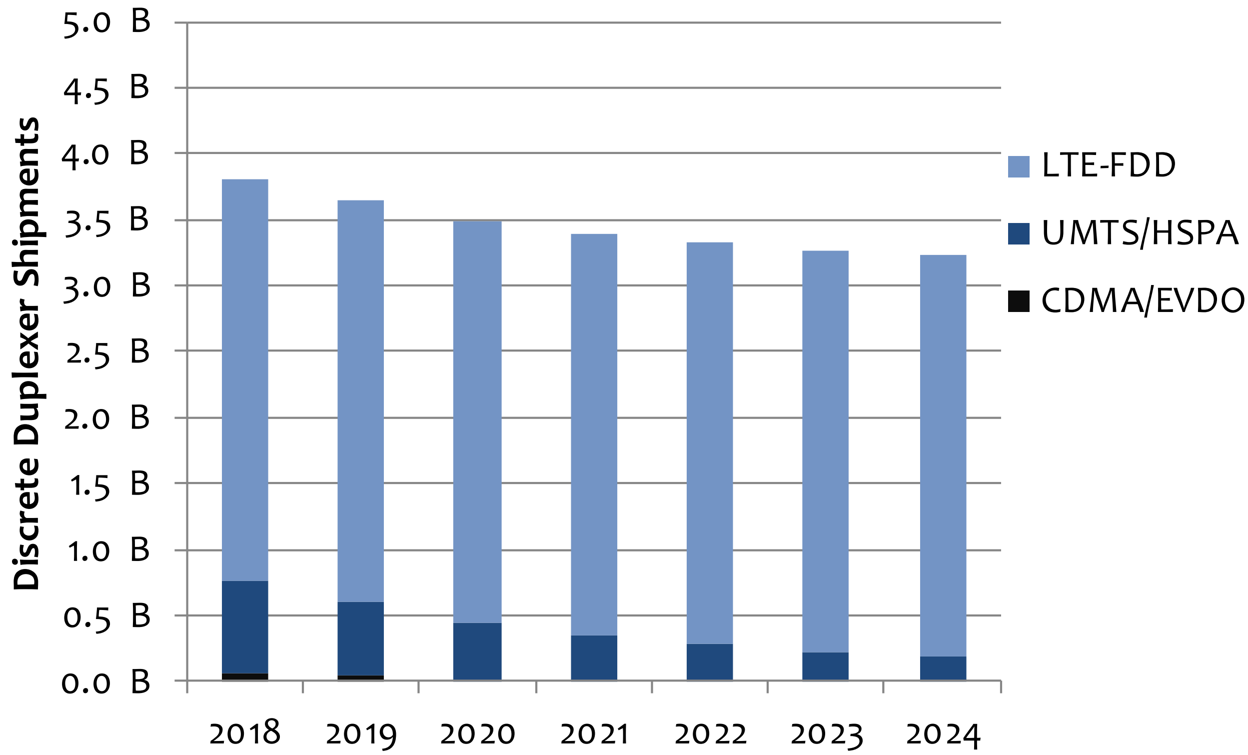


Chart 91: Discrete Duplexer Shipments, by air interface, 2018-2024

Source: Mobile Experts

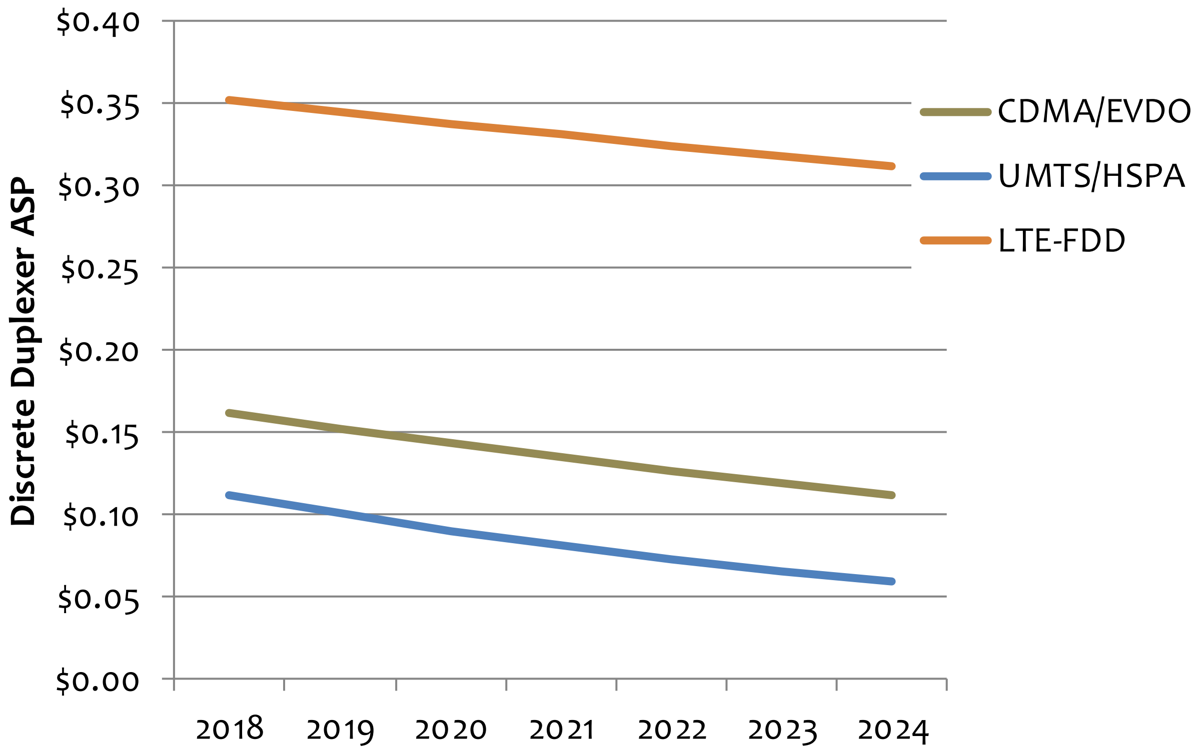


Chart 92: Discrete Duplexer ASP, by air interface, 2018-2024

Source: Mobile Experts

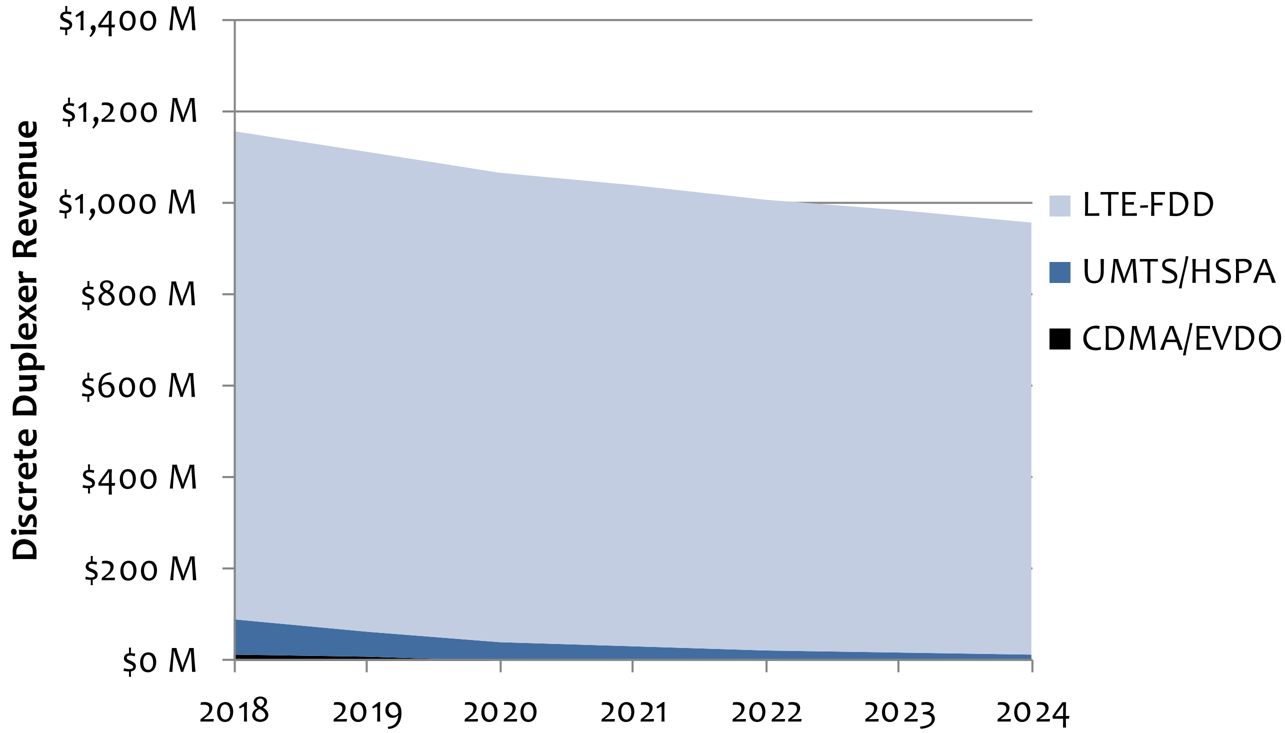


Chart 93: Discrete Duplexer Revenue, by air interface, 2018-2024

Source: Mobile Experts

The revenue per discrete filter die is has declined for some time, but new high-performance BPF modules will actually drive an increase in average price per die. The basic SAW filter die, of course, will not increase. But the high-performance TF-SAW, single-crystal BAW, and other wideband BPF solutions will become significant in moving the average upward.

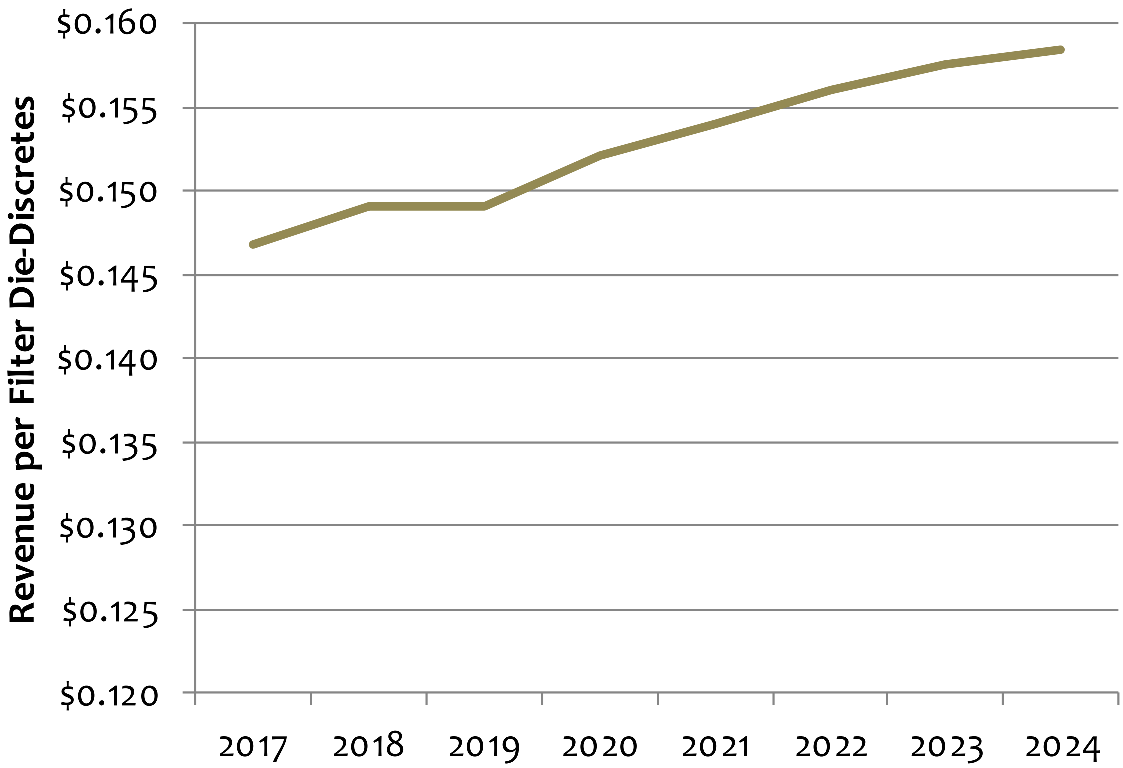


Chart 94: Discrete Filter Revenue per die, 2017-2024

Sources: Mobile Experts. Note: Excluding discrete multiplexers.

Diplexers and Triplexers

Diplexers are found in a lot of smartphones now, with small components to split low and hi bands with the lowest possible loss. These are often discrete devices that live near the antenna and don't lend themselves to integration with either the low-band or high-band modules. This market shows no signs of slowing, as mid-tier and entry level smartphones will also adopt diplexers to break up the bands.

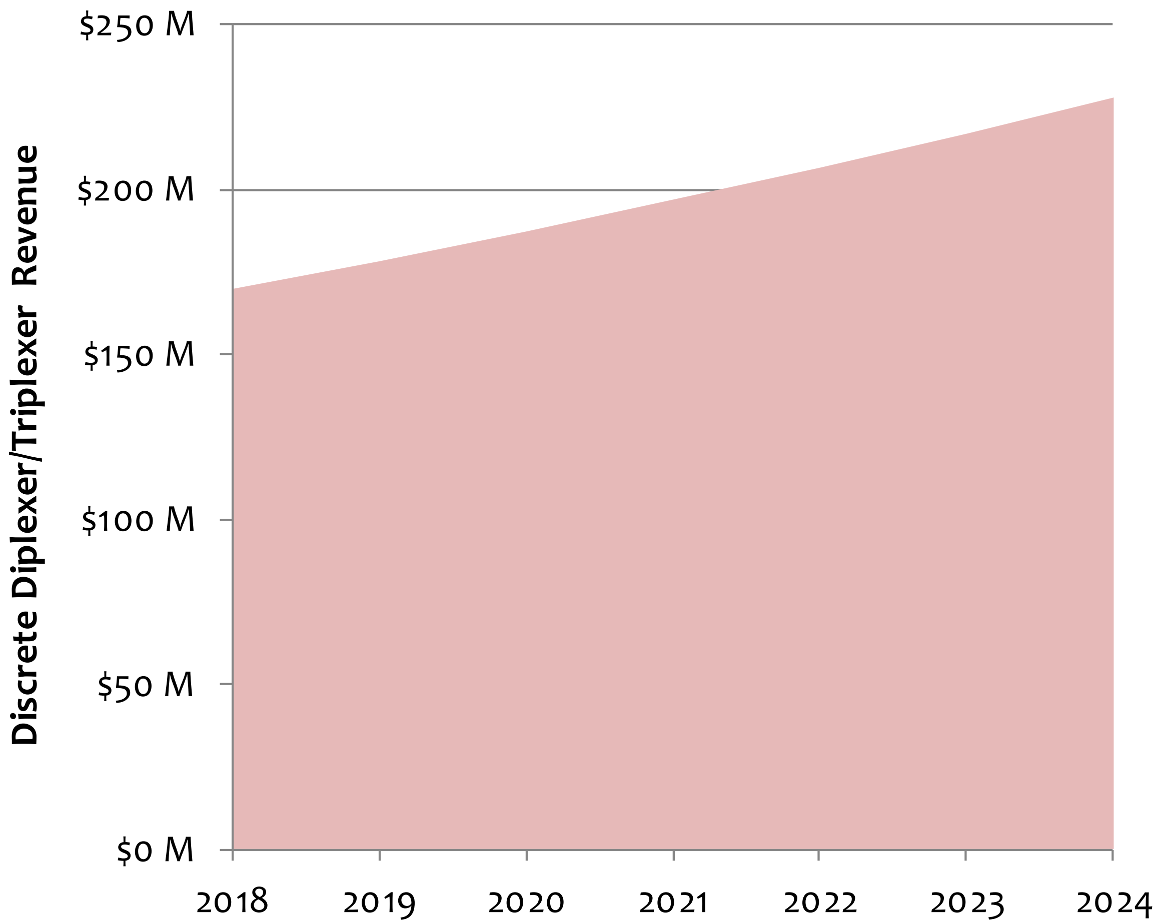


Chart 95: Discrete Diplexer Revenue, 2018-2024

Source: Mobile Experts.

Extractor or Antenna-plexer Filter Outlook

We define an "Antennaplexer" (also known as an Extractor) as a filter assembly (no switches) that separates GPS and 2.4 GHz from the licensed cellular bands, in order to allow antenna sharing for these various receivers.

During 2016 and 2017, several flagship level models adopted this approach, and the convenience of the shared antenna has strong appeal to other handset vendors as well. Adoption by Chinese vendors will drive strong growth for this component type. The level of difficulty for this filter justifies a high selling price, so revenue growth in this area is solid.

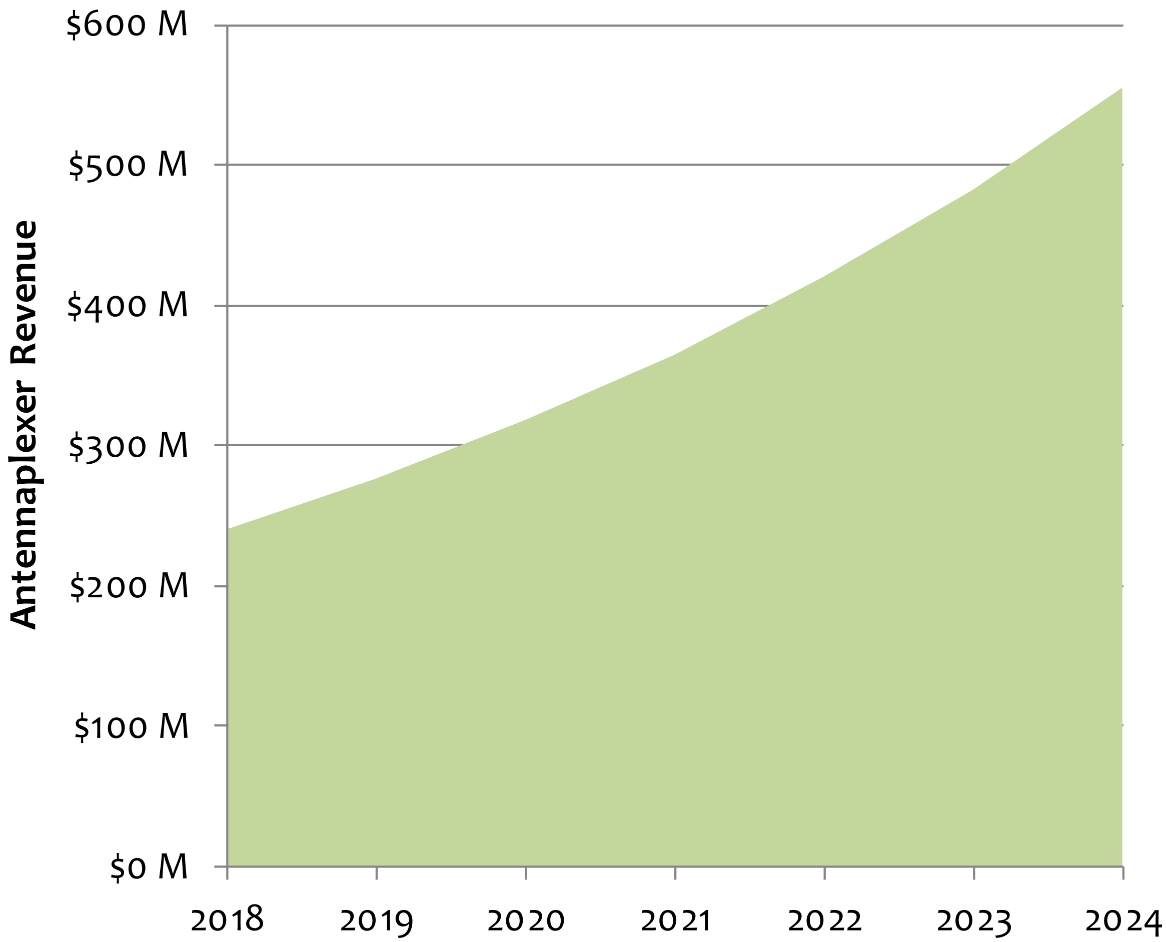


Chart 96: Extractor or Antennaplexer Filter Revenue, 2018-2024

Source: Mobile Experts.

Quadplexer/Hexaplexer/Multiplexer Outlook

In flagship platforms, quadplexers and hexaplexers have now been integrated into CFEs. In mid-tier handsets, the OEMs may not get the custom support that Apple or Samsung get, so we see discrete multiplexers used with MMPA components instead.

Most of the discrete multiplexers are built with BAW or TC-SAW technology, with a few FBAR devices for the high-performance mid-hi band applications.

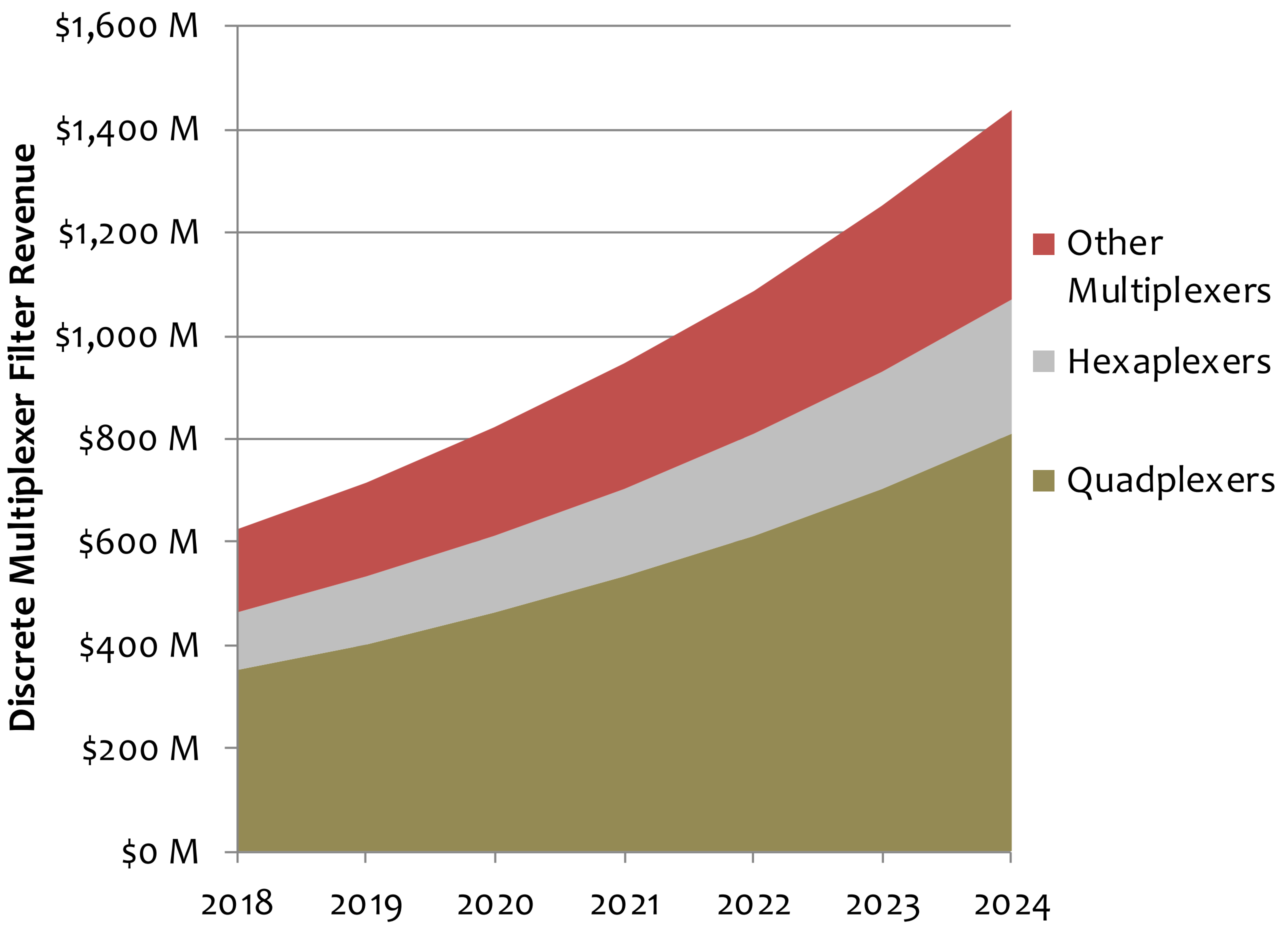


Chart 97: Discrete Quadplexer, Hexaplexer, and Multiplexer Revenue, 2018-2024

Source: Mobile Experts

Discrete Switch Outlook

Many different switches are used in mobile handsets, for multiple purposes: band switching, T/R switching, and tuning. Note that Mobile Experts does not count antenna aperture tuning in the "discrete switch" category, since we count those in the "tuning" segment. Discrete switches refer to band selection switches and antenna transmit/receive switches.

Discrete switches are less common than switches integrated into FEMs, but for example discrete switches are used for band selection in feature phones and some low-tier smartphones. T/R switches are almost universally integrated into Tx Modules or other FEMs, although some discrete implementations of single-band 5G TDD systems could use a separate T/R switch.

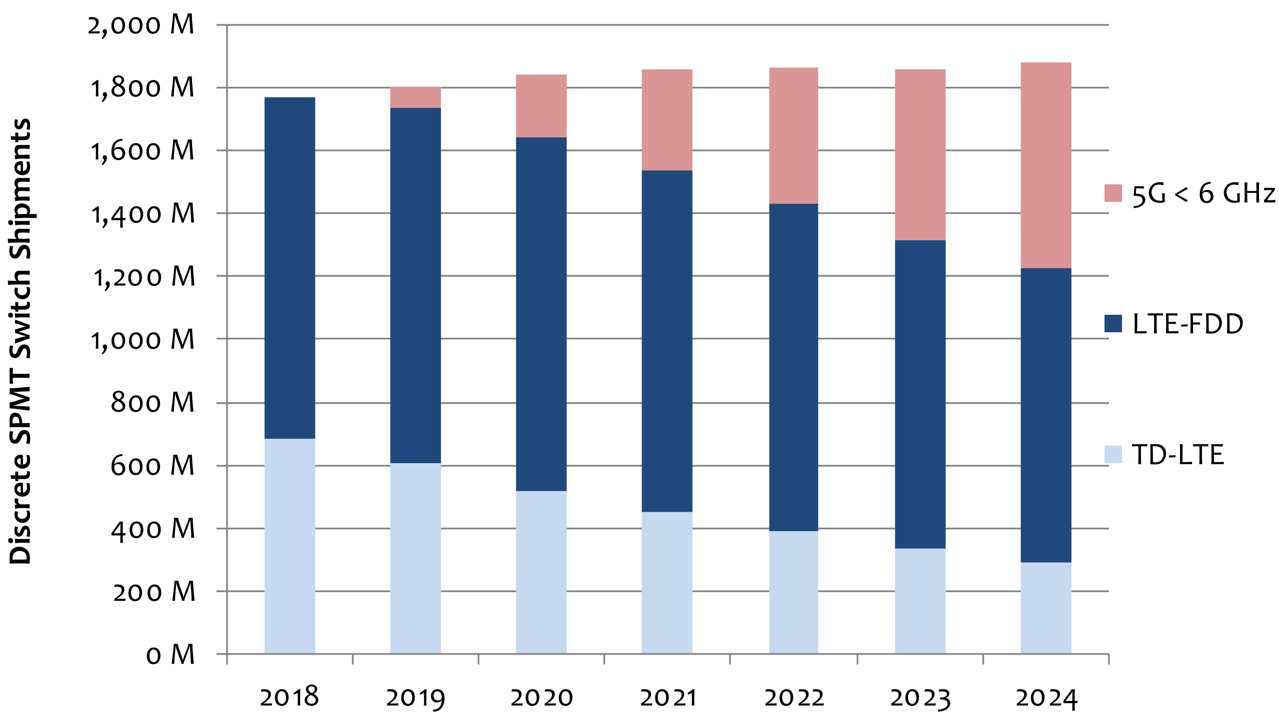


Chart 98: Discrete SPMT switch shipments, 2018-2024

Source: Mobile Experts

Price erosion is pretty simple for the discrete switch market, as multiple companies can meet the requirements with various different process technologies… no shortage of competitors even though this is a low-profile business area.

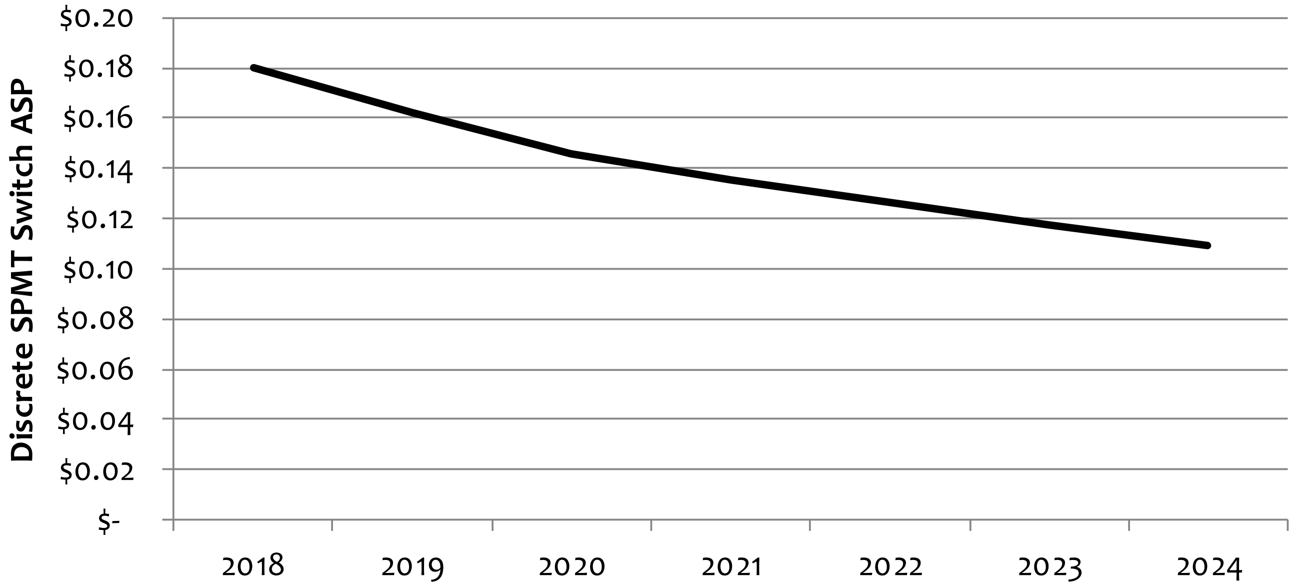


Chart 99: Discrete SPMT Switch ASP, 2018-2024

Source: Mobile Experts

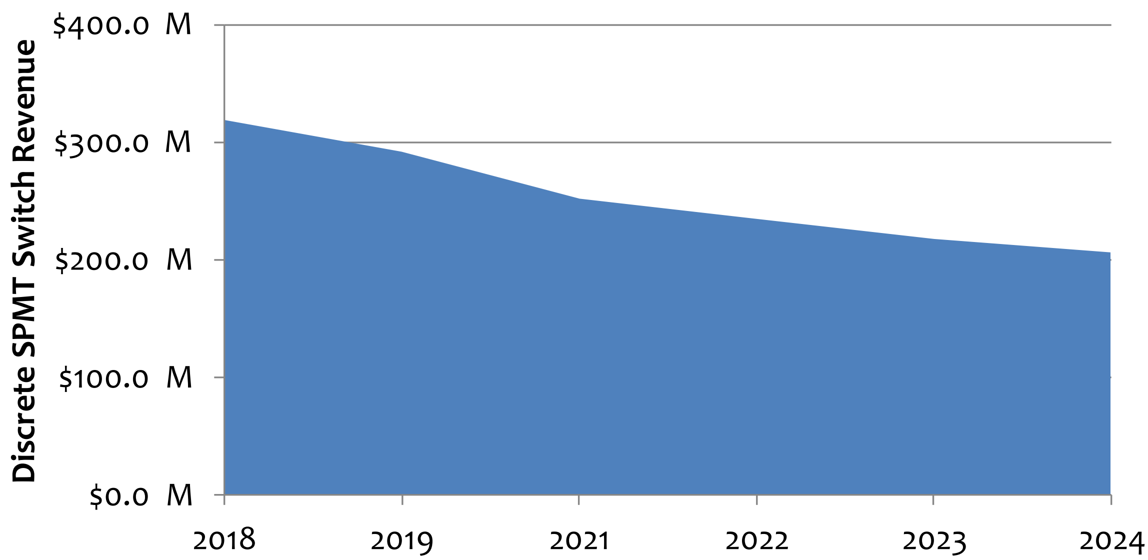


Chart 100: Discrete SPMT Switch Revenue, 2018-2024

Source: Mobile Experts

Transfer Switches

The more interesting opportunity in the switch market comes in the form of transfer switches, which are used to 'swap' antennas. In the event of a poor match on one antenna, the handset can "swap" the antennas so that the main antenna and MIMO/diversity antennas are substituted. This improves uplink performance in cases where a single transmit chain is available, and obviously is less important for Uplink MIMO. This concept has already become entrenched with 2x2 MIMO, but with 4x4 MIMO things gets more complex and lossy, so there's room for innovation here.

Adoption in tablets and PCs will be generally one transfer switch per terminal, because the need for high and low band multi-band performance will not be as critical as a smartphone. In premium smartphones, some platforms will adopt more than one transfer switch, so the number of units will keep rising in the 2 billion range.

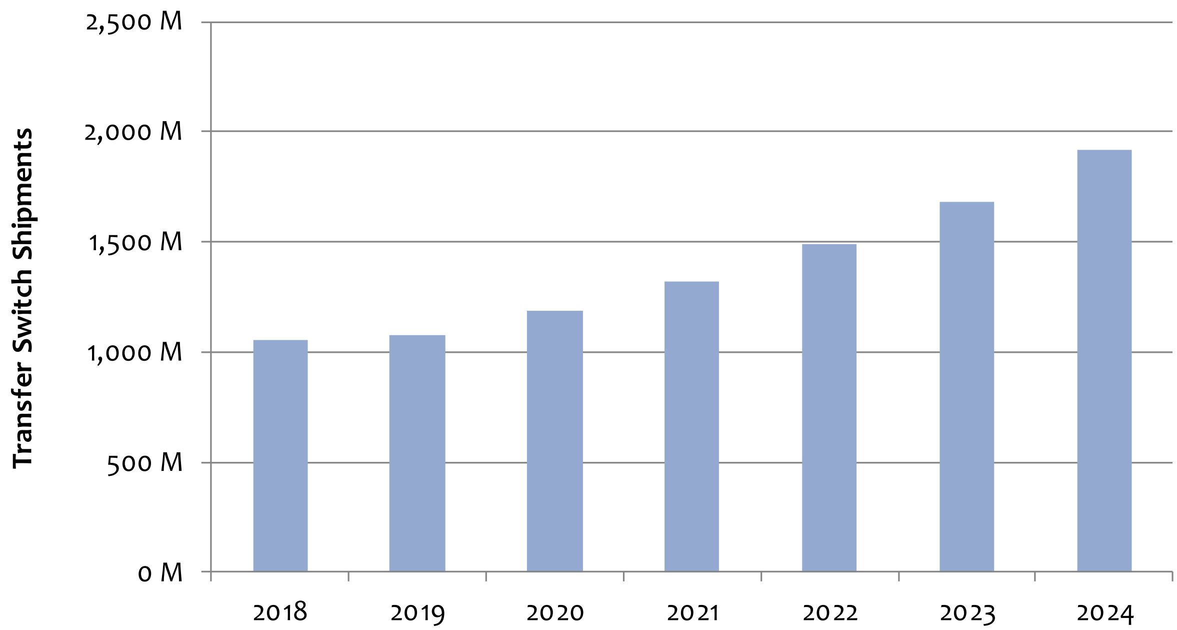


Chart 101: Transfer Switch Shipments, 2018-2024

Source: Mobile Experts

MEMS switches look like a good solution for the transfer switch application, because they can provide lower loss than SOI or other semiconductor switches. Based on the rise of complexity and significant adoption of MEMS, we are anticipating a rise in pricing for transfer switches.

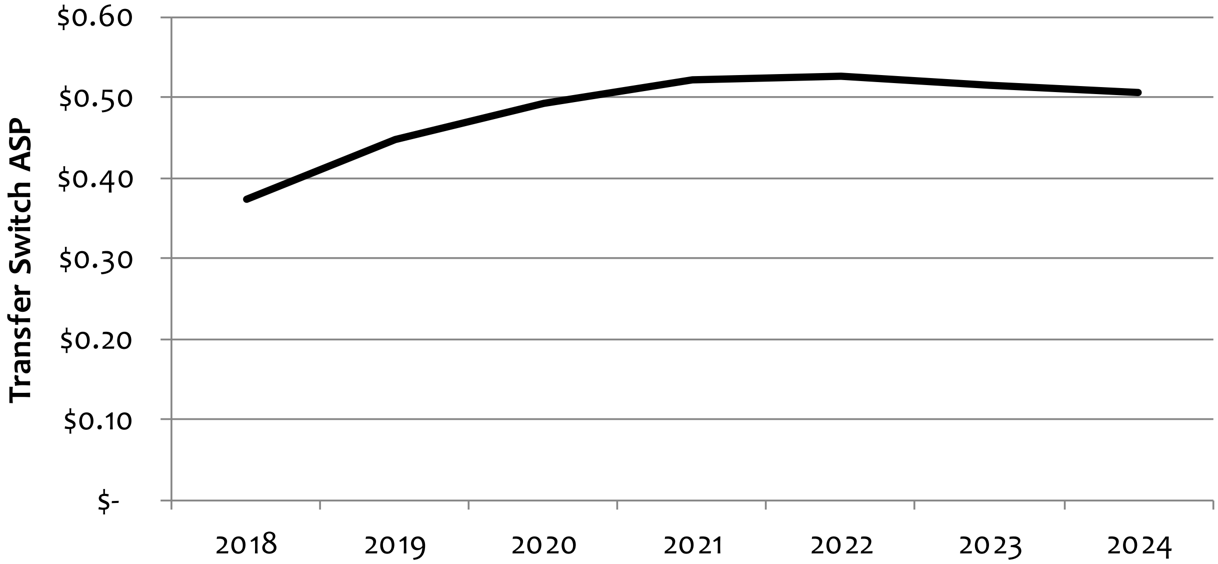


Chart 102: Transfer Switch ASP, 2018-2024

Source: Mobile Experts

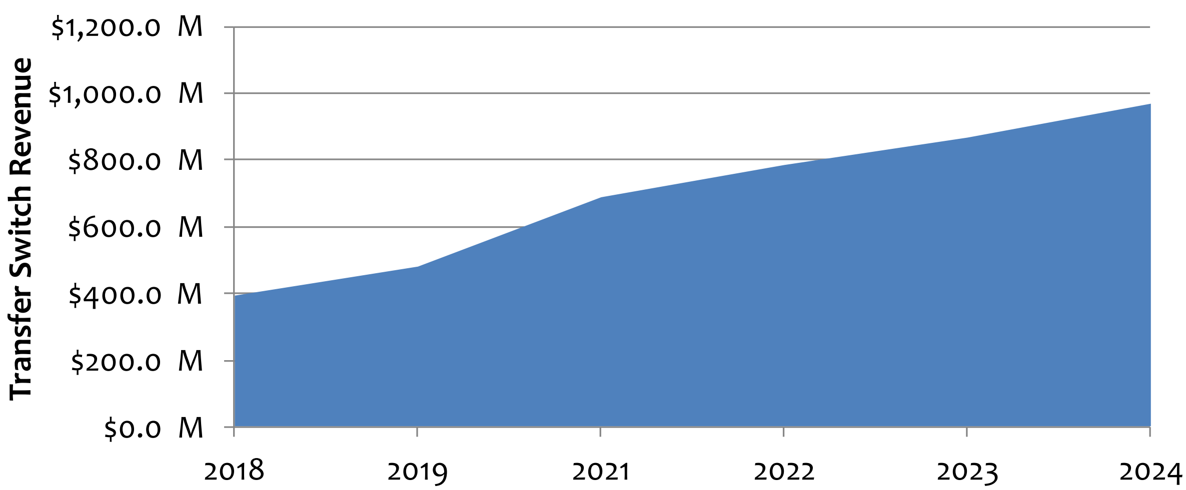


Chart 103: Transfer Switch Revenue, 2018-2024

Source: Mobile Experts

Growth in the transfer switch market will be balanced by declines in the band switching market caused by price erosion. The overall discrete switch market will stay pretty flat.

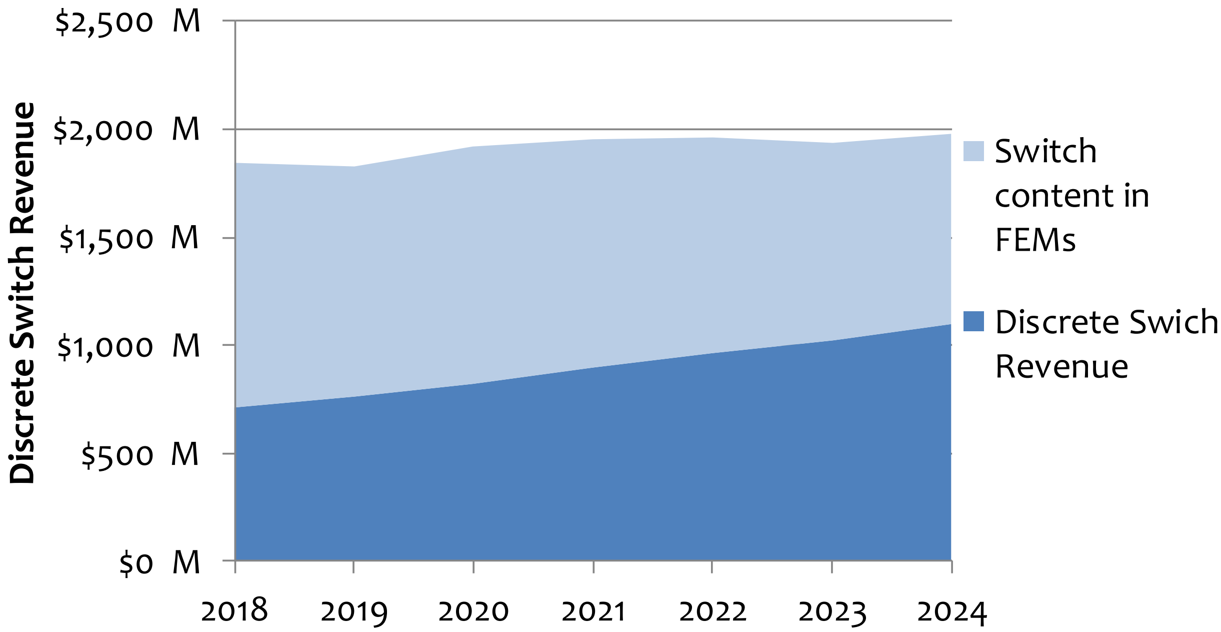


Chart 104: Overall Switch Revenue, by Discrete vs Integrated, 2018-2024

Source: Mobile Experts

Tuning Element Outlook

Low-band antennas have used switches and capacitors for several years to move the resonant frequency of the antenna as needed. Things are getting more complex now with high-band tuning and multi-band tuning requirements.

Now, we are seeing that the products are improving to take care of more difficult requirements. MEMS technology in particular is growing quickly and moving from the low-tier phones into leading platforms.

Impedance tuning is also a good way to enhance performance, but fewer platforms are adopting the impedance-tuning philosophy, so most of the revenue is focused on aperture/frequency tuning.

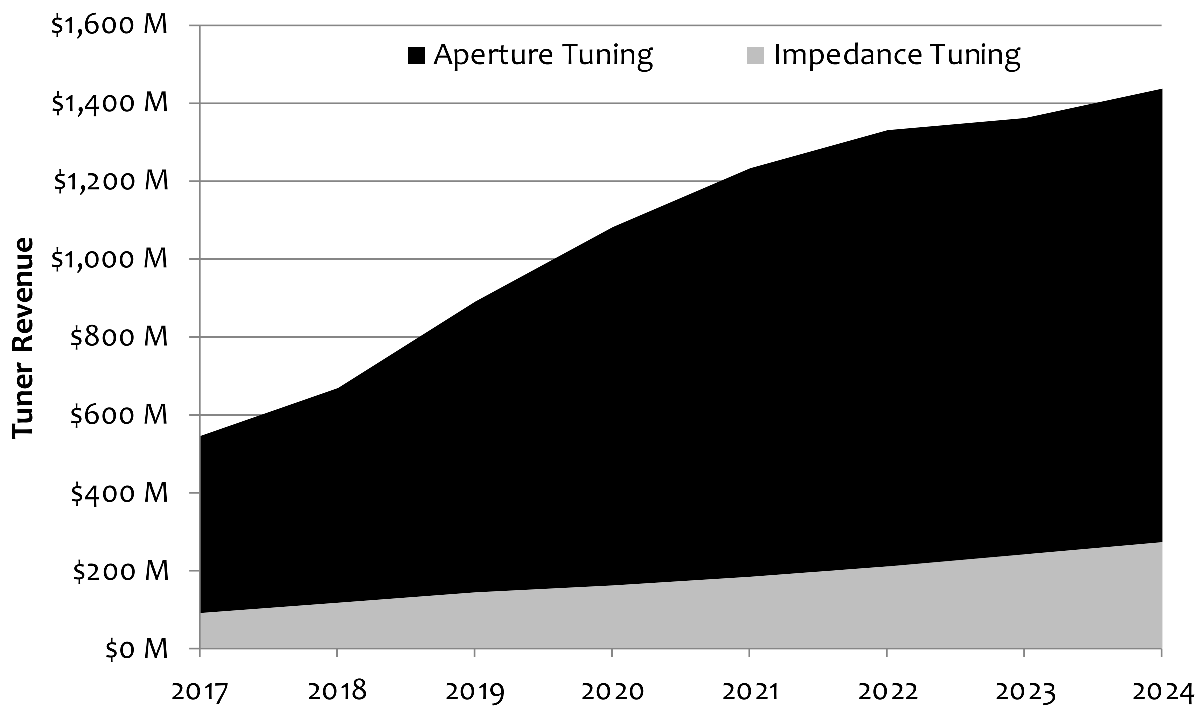


Chart 105: Overall Tuner Revenue, by Frequency Tuning vs Impedance Tuning, 2017-2024

Source: Mobile Experts

Aperture Tuning Outlook

Aperture tuning has a solid baseline business in the low-band antenna application. Growth in the low bands will slow down, but adoption for mid-to-high bands is heating up and will drive significant growth due to higher numbers and higher performance expectations.

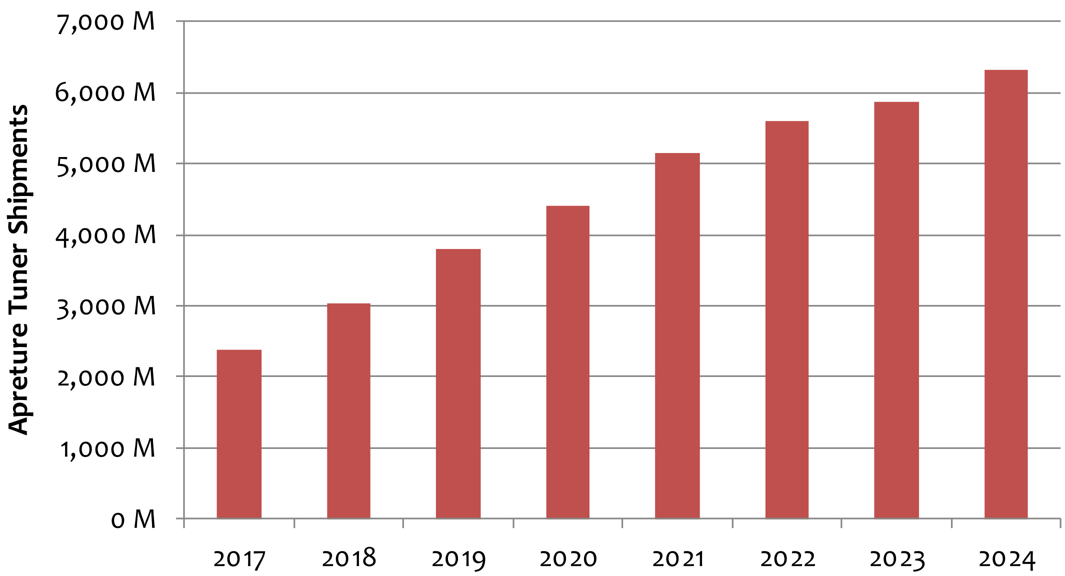


Chart 106: Forecasted Aperture Tuning Shipments, 2017-2024

Source: Mobile Experts

MEMS has now proven its performance advantages in multiple areas, and has field experience that proves it's a technology that is ready for prime time. MEMS improves on both "off" capacitance, and "on" resistance (C_{off} and R_{on}), and can handle higher voltages than semiconductor switches, which allows the tuner to be placed in a more flexible and effective way. For these reasons, we see MEMS adoption growing quickly for the next few years.

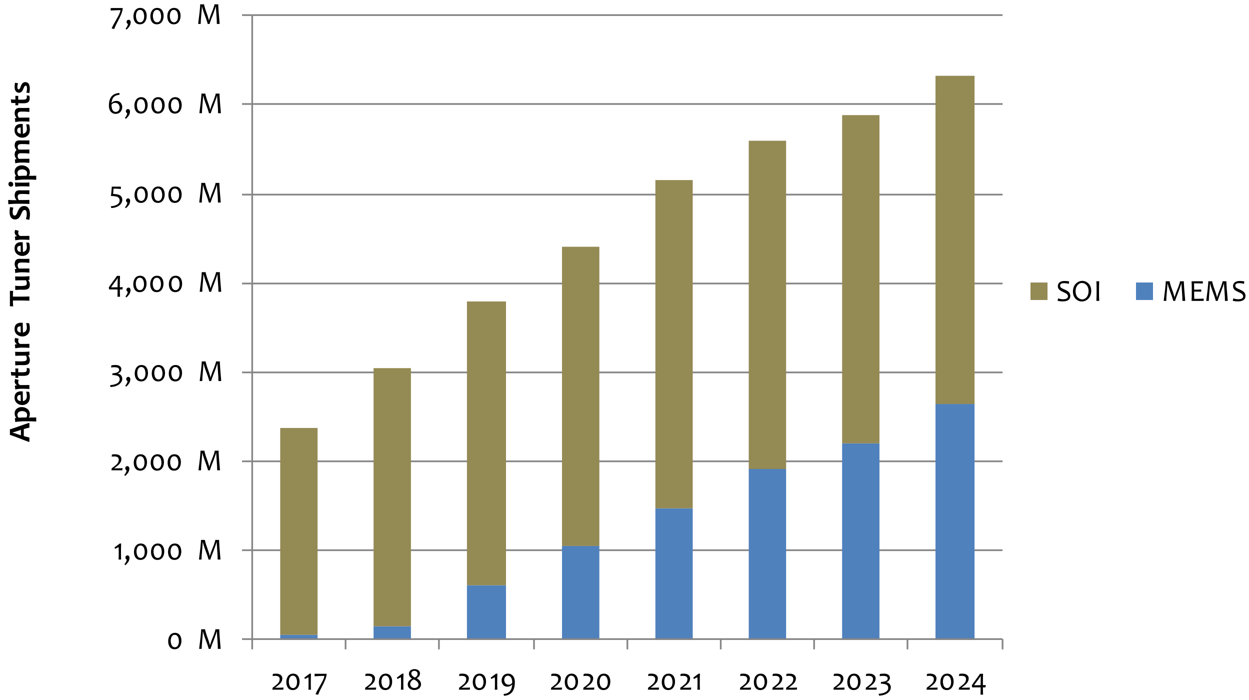


Chart 107: Forecasted Aperture Tuning Shipments, by process technology, 2017-2024

Source: Mobile Experts

SOI tuners are sold for very low prices—because there is little barrier to entry in the SOI market. However, the MEMS tuners are highly specialized and require a great deal of new process development. The MEMS devices have been able to achieve much higher pricing than SOI in the open market due to their much higher performance. MEMS pricing is actually increasing in the near term, as next-generation devices come out with higher performance. We're assuming that some competition will show up for Cavendish in the MEMS market in roughly 2021, forcing normal price erosion.

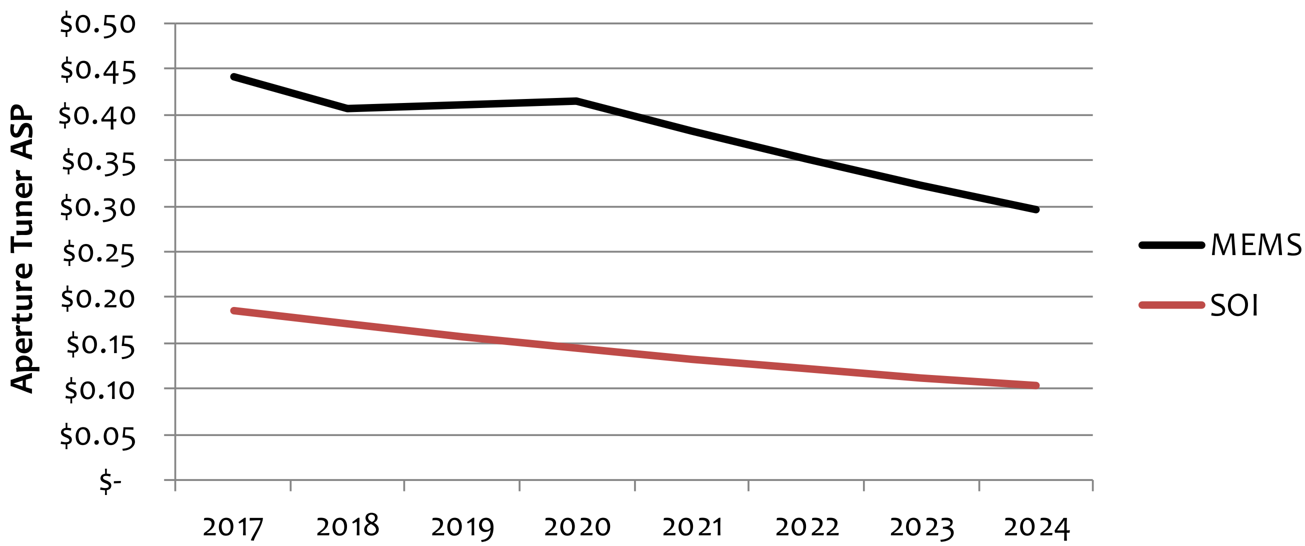


Chart 108: Forecasted Tuner ASP, by process technology, 2017-2024

Source: Mobile Experts

This is one of the bright spots in an otherwise flat RFFE market. Revenue for tuners will continue to grow, as CA and band complexity demand a good match with multiple bands and high-resolution tuning becomes a necessity. The Mobile Experts forecast assumes that rapid adoption across mid- and high-tier smartphone platforms leads to quick growth in 2019-2021, but after adoption happens the growth will slow down.

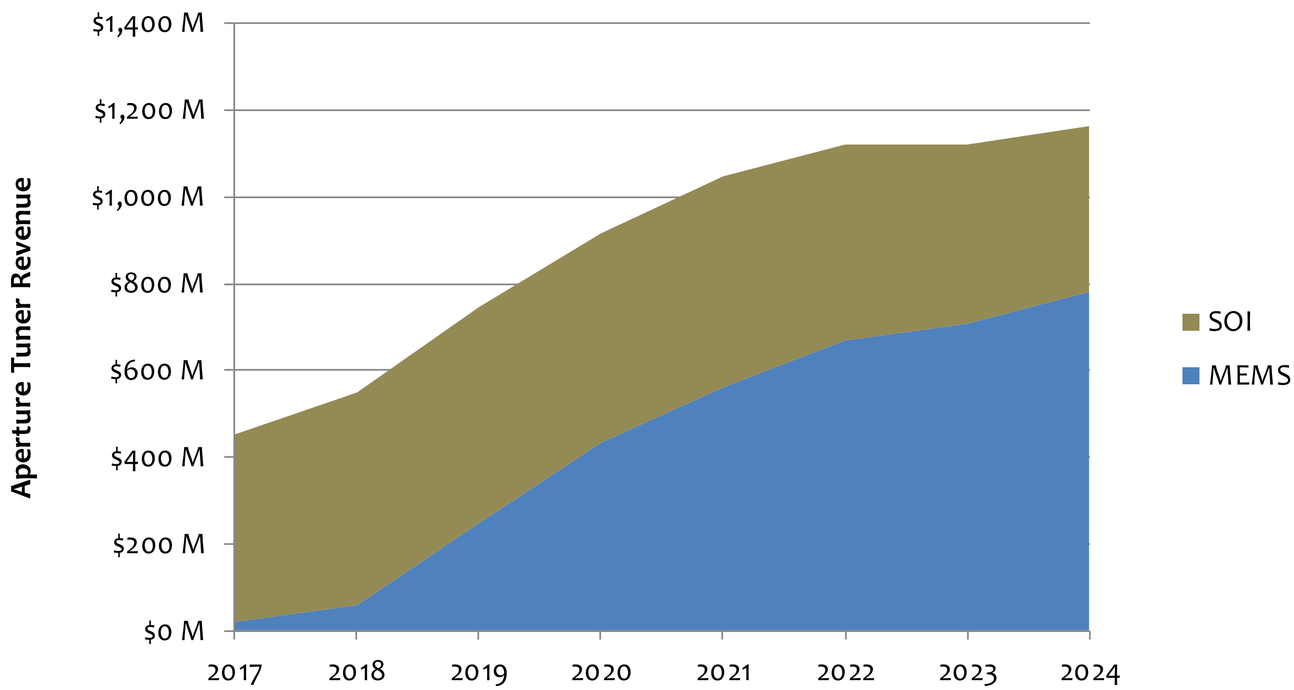


Chart 109: Forecasted Aperture Tuning Revenue, by process technology, 2017-2024

Source: Mobile Experts

Impedance Tuning Outlook

Impedance tuning has not taken off as fast as aperture tuning, because the benefits are not as clearly shown in the testing used to certify phones. Typically conducted acceptance testing is the key test, so impedance-match tuning does not show a benefit---even though the benefits in the real world are quite significant.

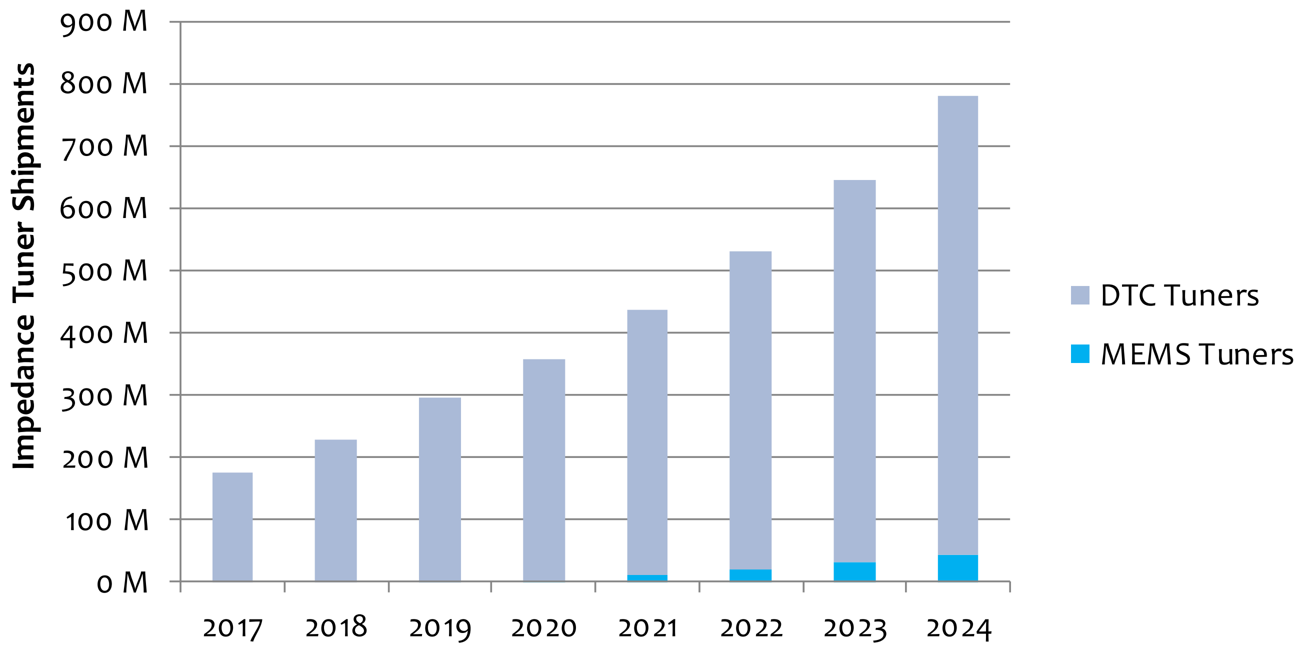


Chart 110: Forecasted Impedance Tuner Shipments, by process technology, 2017-2024

Source: Mobile Experts

We anticipate adoption of MEMS tuners at some point in the future, as MEMS devices have higher performance than SOI tuning capacitor devices. So far, modem vendors have implemented their closed-loop tuning with SOI devices for convenience but eventually we expect the higher performance to make its way into this application.

Pricing for impedance match tuners is a bit higher than aperture tuners, and we expect that relationship to remain in the near future.

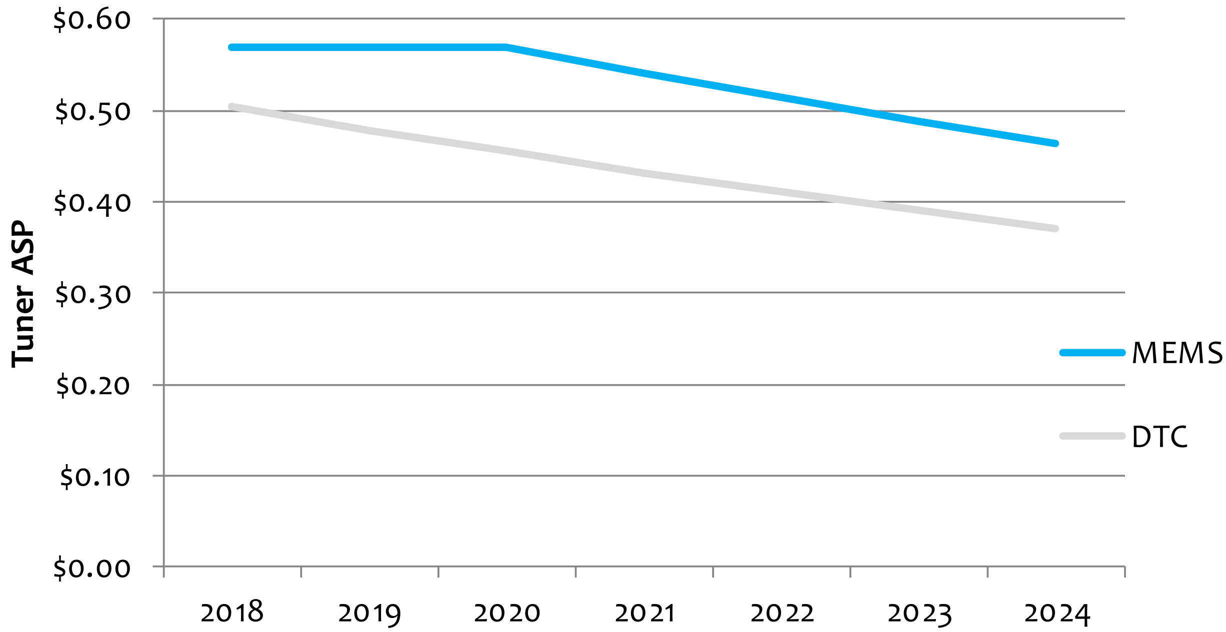


Chart 111: Forecasted Impedance Tuner ASP, by process technology, 2018-2024

Source: Mobile Experts

As high-band antennas start to handle more bands with 5G, we expect the impedance mismatches and uplink performance to be an issue, and some OEMs are likely to start adopting impedance-matching techniques to gain some uplink performance back.

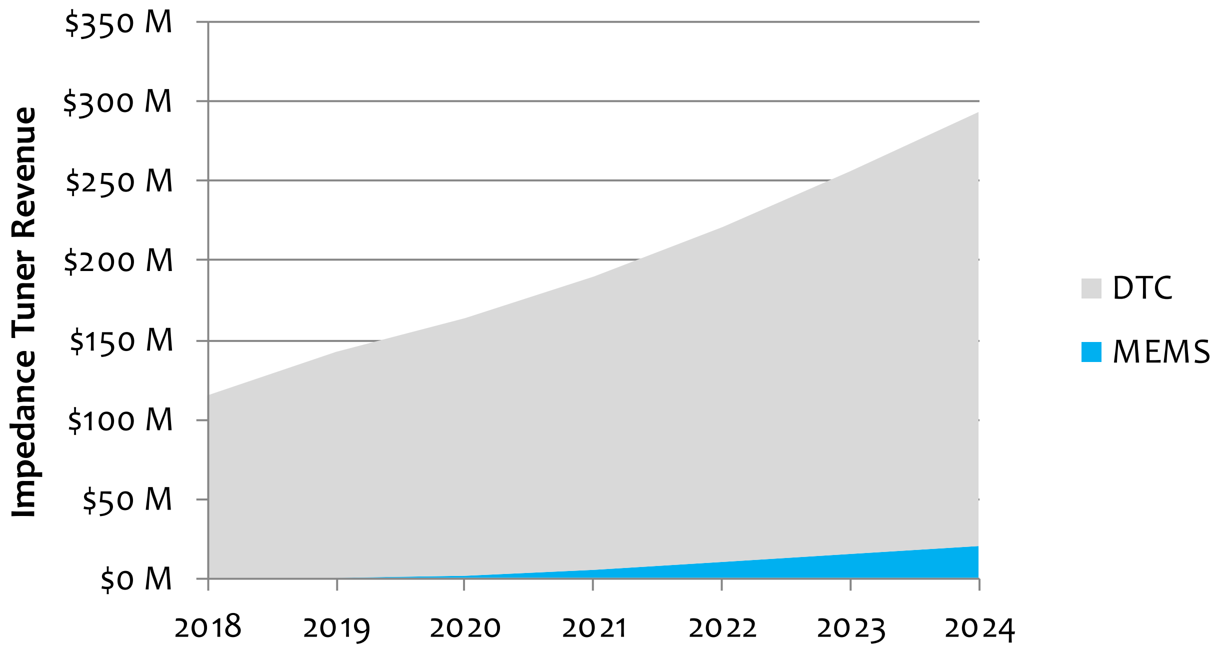


Chart 112: Forecasted Impedance Tuner ASP, by process technology, 2018-2024

Source: Mobile Experts

LNA Outlook

LNAs were removed from mobile phones in the 1990s, but they have returned because the LNA is necessary to overcome the high losses related to high band count. The initial implementation as discrete LNAs has quickly changed over to integration with diversity modules, and now there is integration taking place with CFEs… so LNAs can be found throughout the front end.

The below charts record the remaining number of discrete LNAs sold as separate devices.

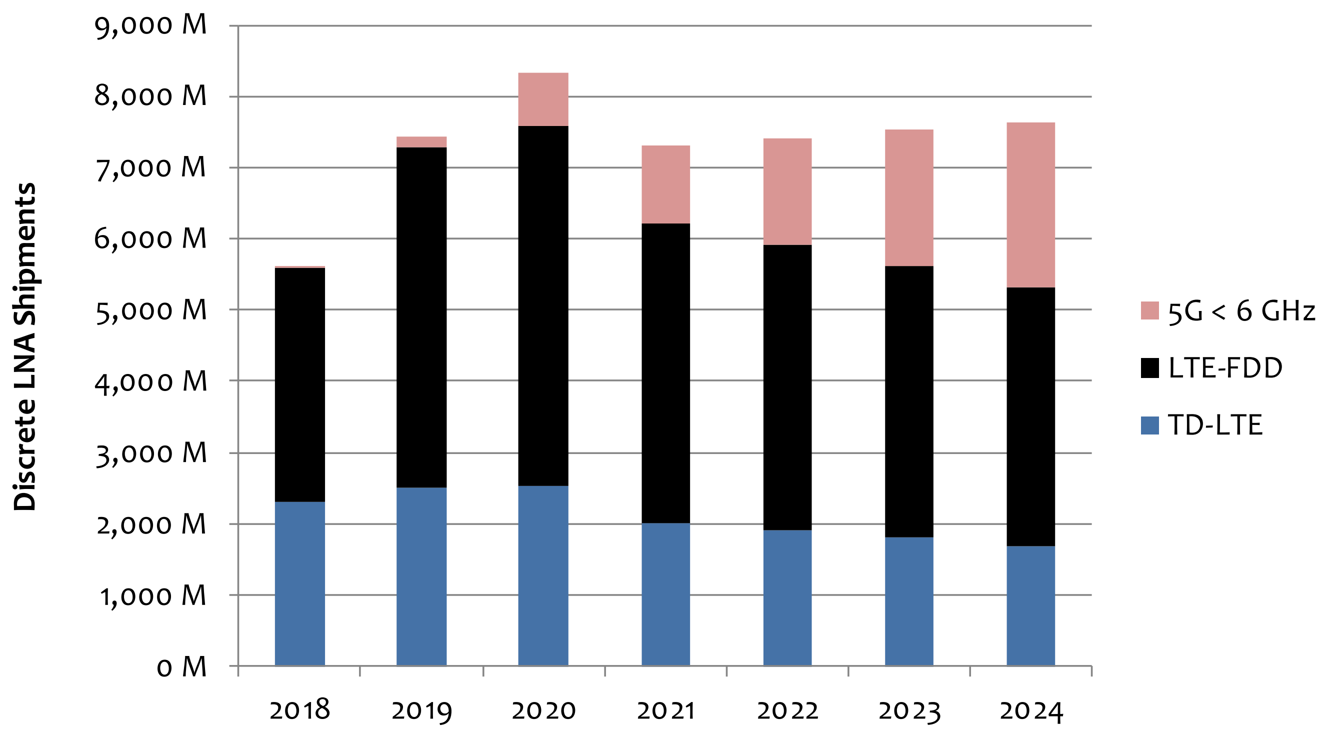


Chart 113: Forecasted Discrete LNA Shipments, by air interface standard, 2018-2024

Source: Mobile Experts. NOTE: Each handset categorized by the highest air interface included

Pricing for LNAs keeps dropping steadily because multiple suppliers can provide these. For discrete LNAs, all kinds of process technologies are in play, including SiGe, SOI CMOS, and GaAs. In the integrated LNA market, the 'integratability' of the LNA with CMOS is important but not as much in the discrete market.

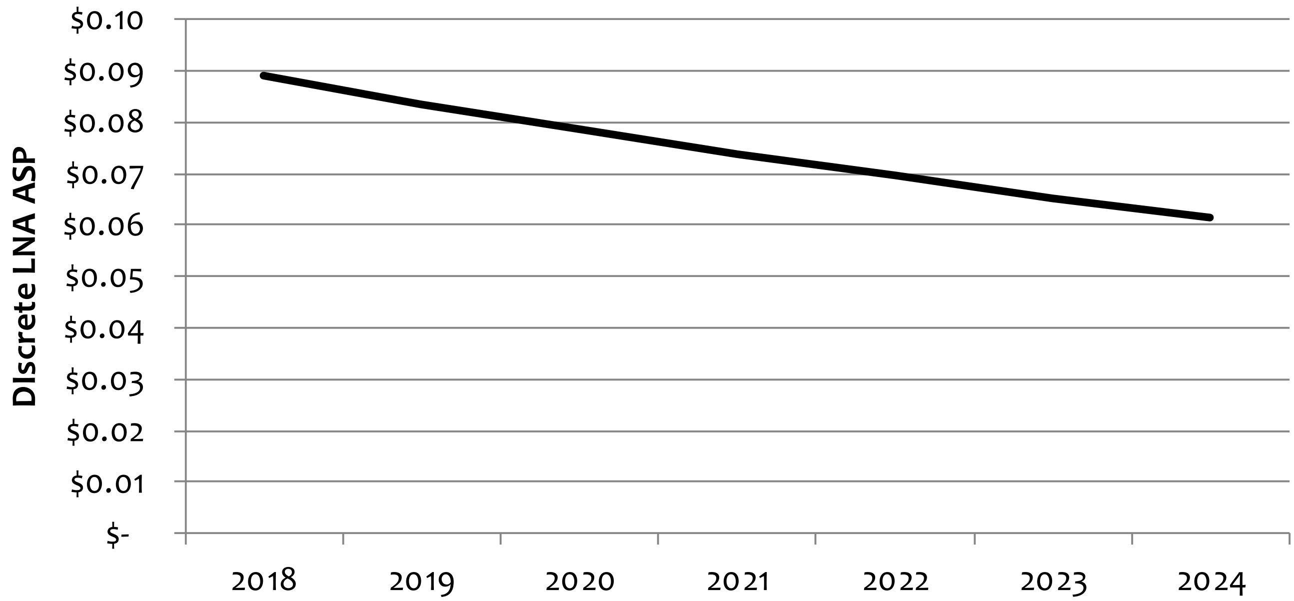


Chart 114: Forecasted Discrete LNA ASP, 2018-2024

Source: Mobile Experts

LNAs embedded within Diversity Modules and CFEs have quickly become the majority of the LNA market. In the future, we expect that the discrete market will lag the market because most LNAs will be integrated with Diversity Modules or PA-based FEMs.

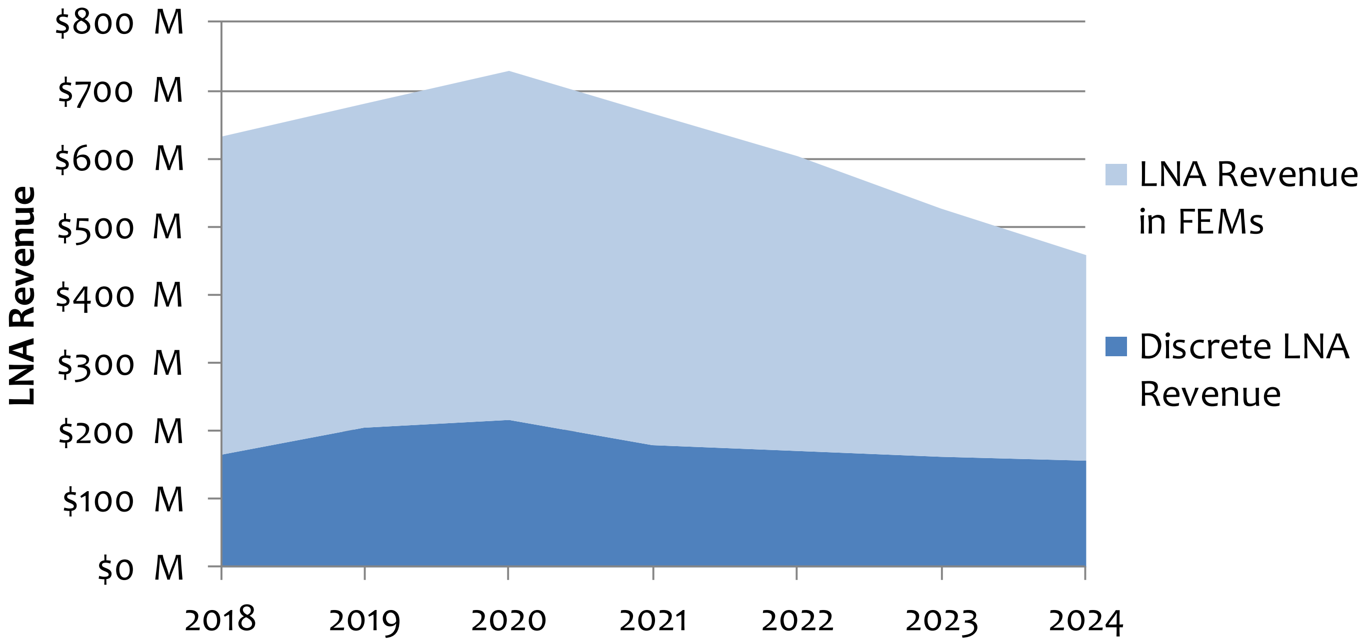


Chart 115: Forecasted LNA Revenue, 2018-2024

Source: Mobile Experts

Millimeter Wave Module Forecast

The only mm-wave sub-array on the market now includes 4 dual-polarized elements, so we are using this basic building block as our reference point. In our forecast, we assume that smartphones will use either three or four sub-arrays. Hotspots or CPE units will use 4 to 8 sub-arrays, with some options in between. In fact, we expect some deviation from the 4-element subarray, but for simplicity we are assuming the 4-element building block.

For multiple reasons, we expect the hotspot or CPE to be the primary mm-wave radio platform instead of the smartphone. This conclusion is only tentative, as many OEMs in the industry are intent on cramming the mm-wave function into their handsets. We are currently waiting to see which option the operators will actually subsidize and promote, and we expect to have improved data from the market by the end of 2019.

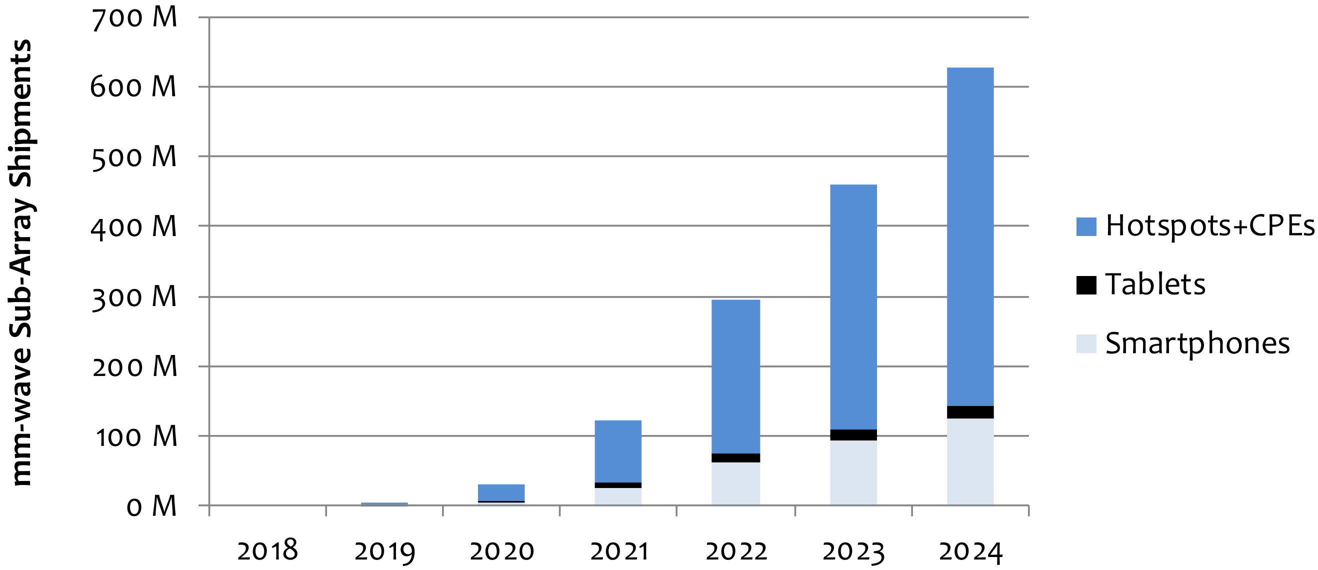


Chart 116: Millimeter-wave RFFE sub-array forecast, by platform type, 2018-2024

Source: Mobile Experts

The pricing for mm-wave modules is difficult to estimate today, with only one vendor on the market. We expect Qualcomm to bring pricing down to a level that allows for market adoption, not to hold on to artificially high pricing. Offsetting the reduction, of course, will be pressure for higher performance, wider bandwidths, and new features. Overall we expect to see the 4-element subarray start in the range of $5-6, then transition lower. Other (presumably more complex) sub-arrays are likely to be priced a bit higher.

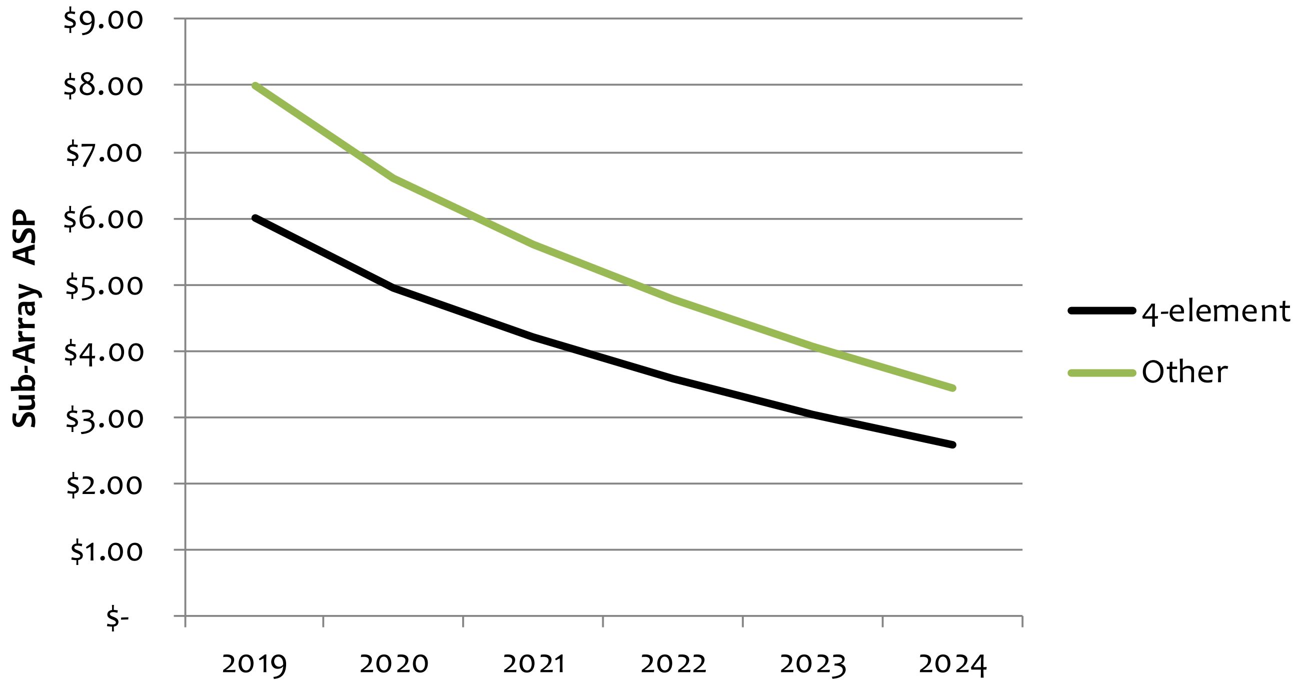


Chart 117: Millimeter-wave RFFE module ASP, by number of elements, 2018-2024

Source: Mobile Experts

Overall revenue for mm-wave modules will rise quickly from zero to a billion dollars. Currently, we expect the 4-element subarray module to dominate the market, but that could easily change. The main wildcard question is whether the operators will promote mm-wave smartphones, or whether the operators will prefer hotspots. As the choice of platform becomes clear, the 4-element subarray could change to a different configuration.

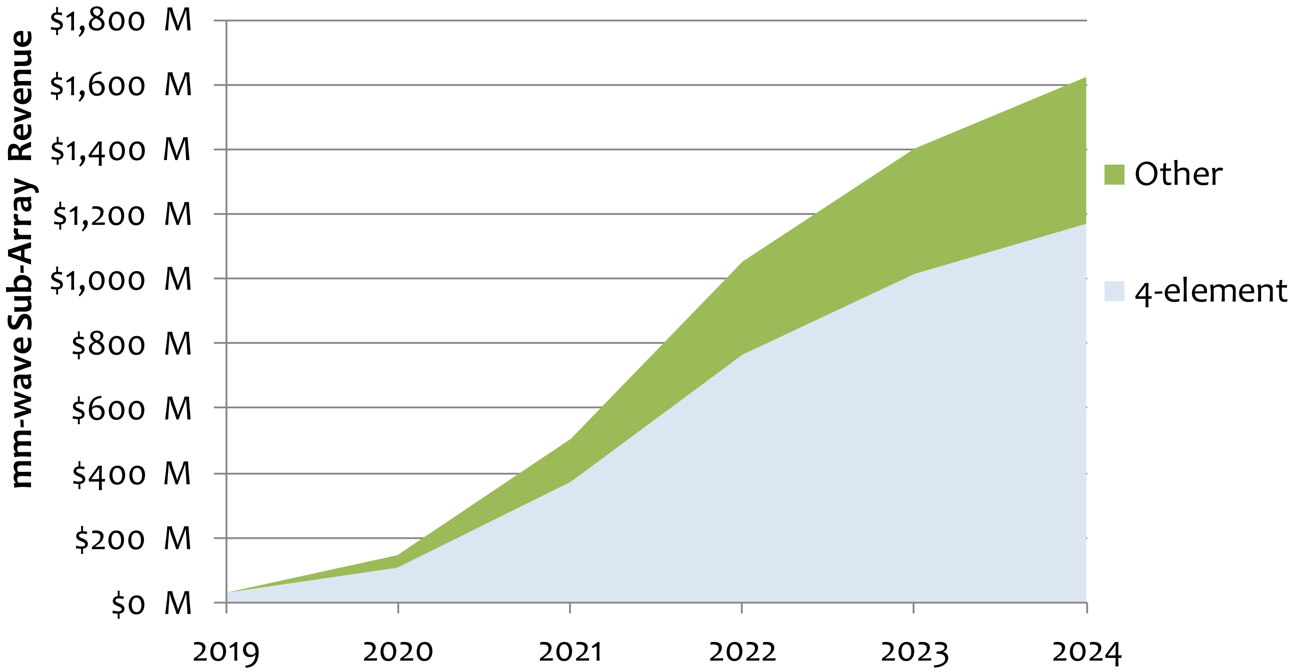


Chart 118: Millimeter-wave RFFE Module Revenue, by number of elements, 2018-2024

Source: Mobile Experts

MIMO Outlook

The handset world is quickly moving into 4x4 MIMO for the downlink, and we already see 2x2 MIMO arrangements for all LTE smartphones as well as most LTE IoT devices.

We're not expecting a step up to 8x8 MIMO in bands below 6 GHz.

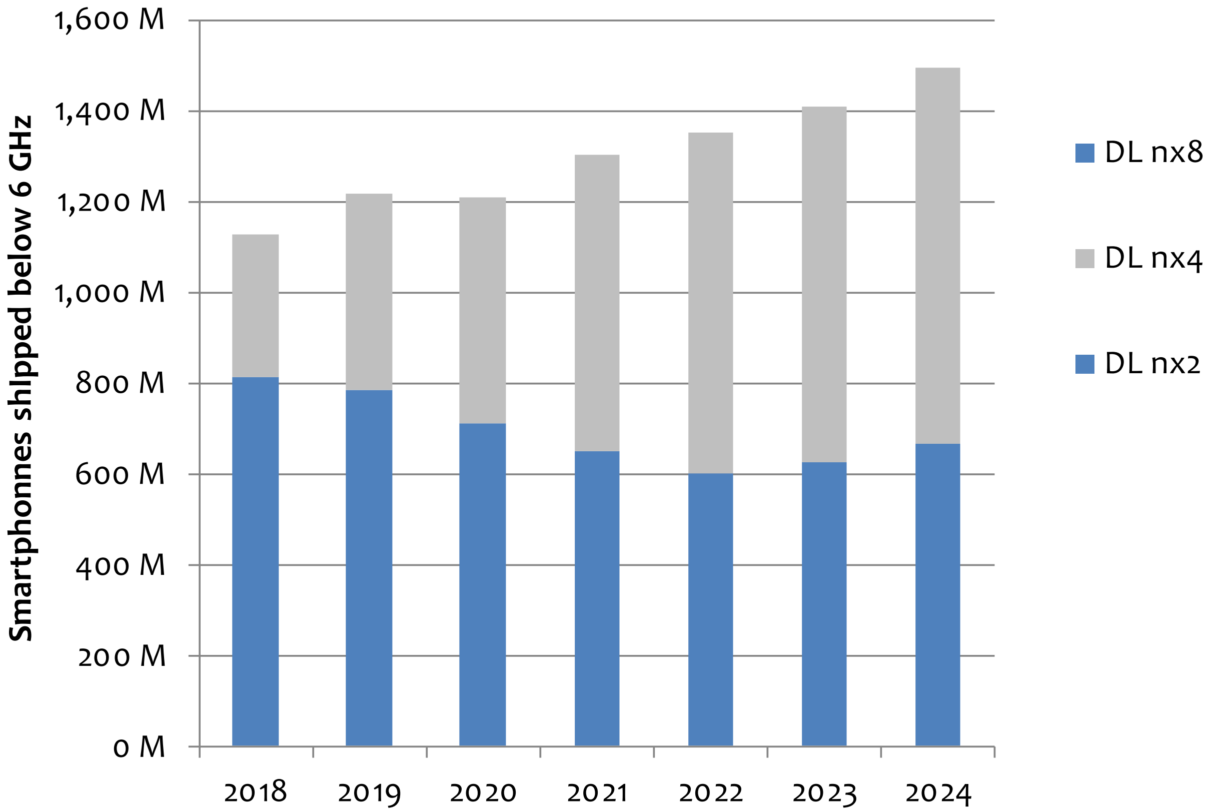


Chart 119: Smartphone MIMO Forecast, 2018-2024

Source: Mobile Experts

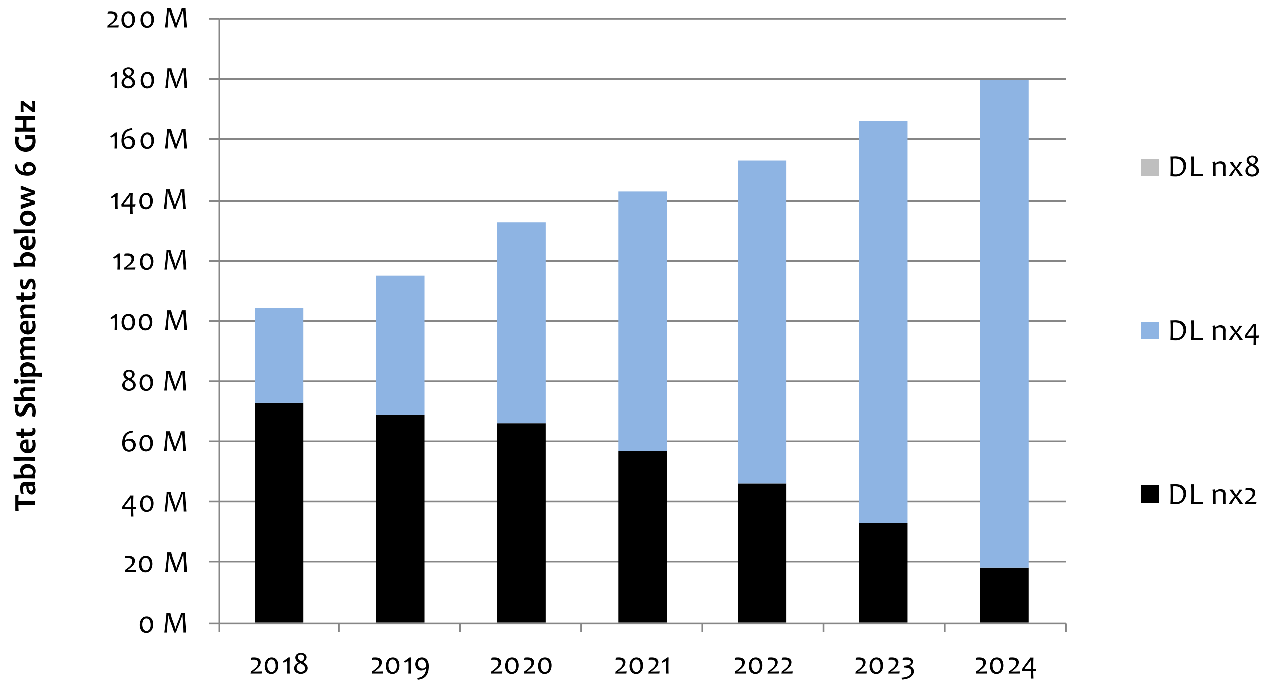


Chart 120: Tablet MIMO Forecast, 2018-2024

Source: Mobile Experts

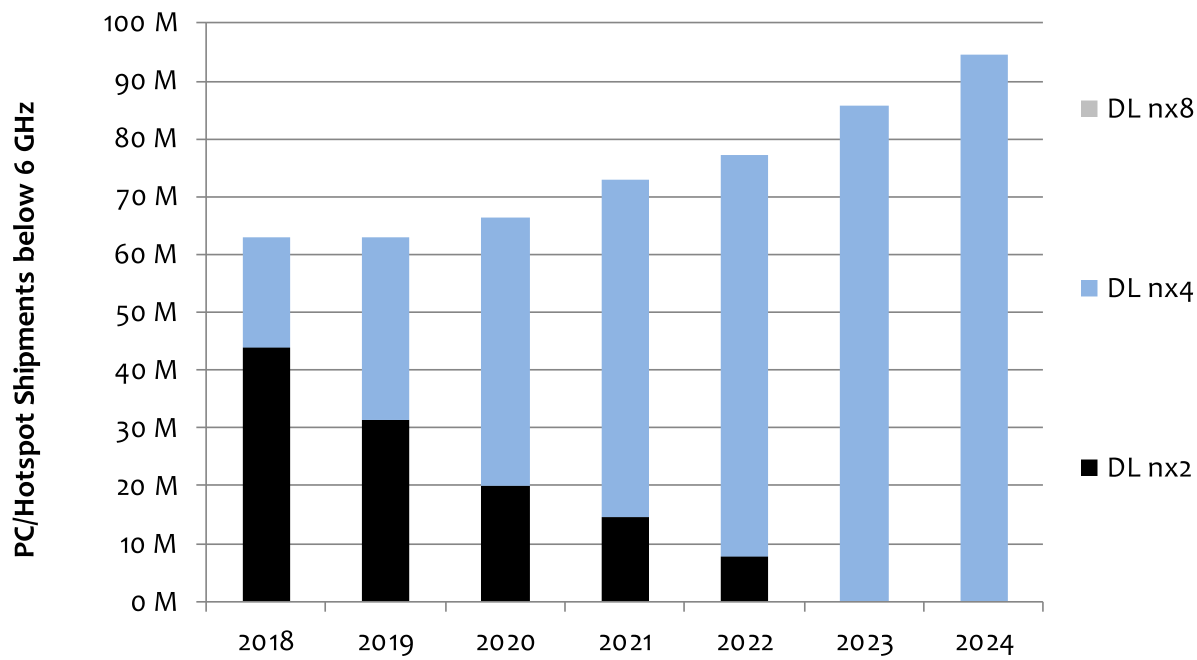


Chart 121: PC and Hotspot MIMO Forecast, 2018-2024

Source: Mobile Experts

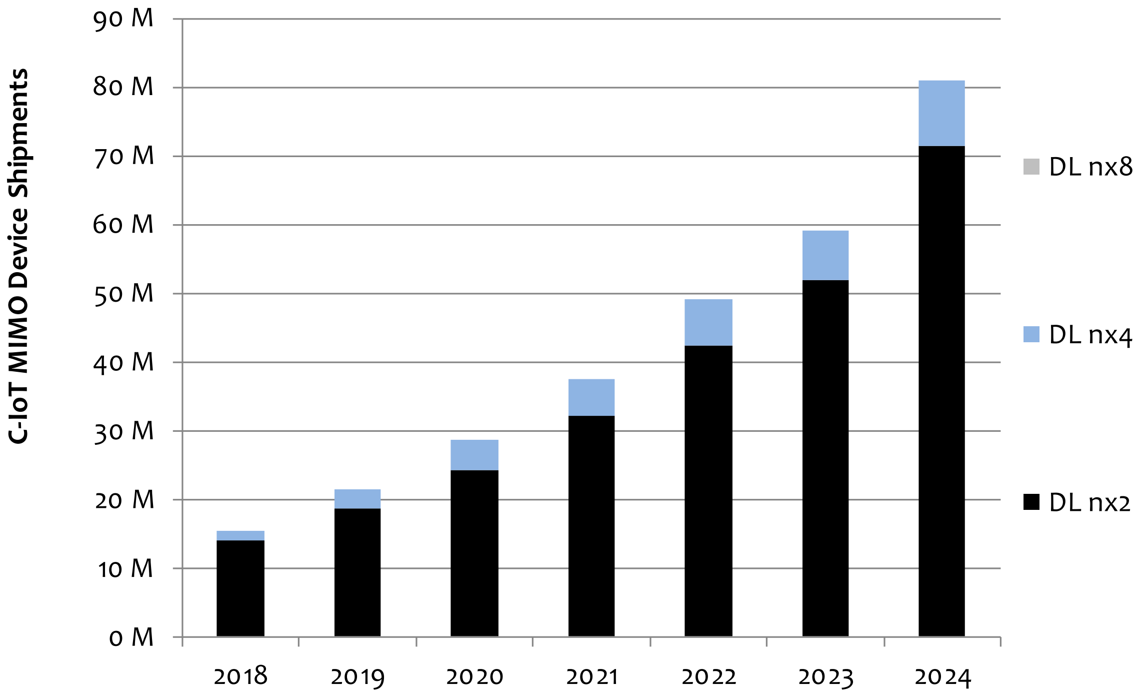


Chart 122: Cellular IoT Devices, MIMO Forecast, 2018-2024

Source: Mobile Experts

Uplink MIMO is also coming to the handset along with 5G, so we anticipate a rise in Uplink MIMO (keep in mind that this is likely to be active only in a few bands)

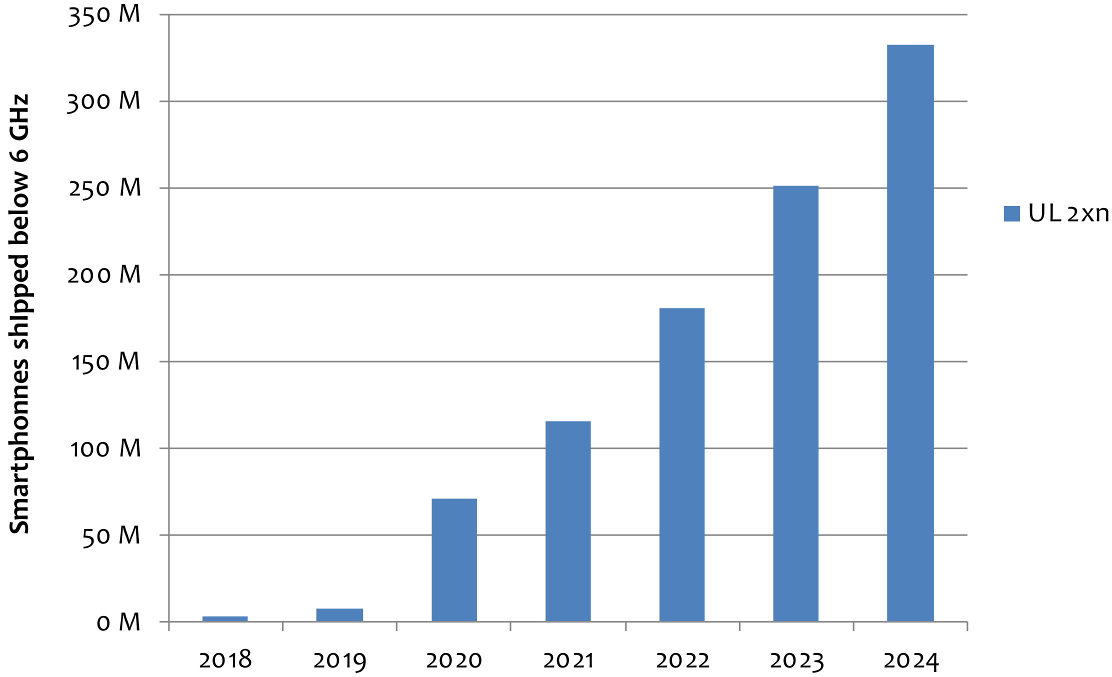


Chart 123: Smartphones, Uplink MIMO Forecast, 2018-2024

Source: Mobile Experts

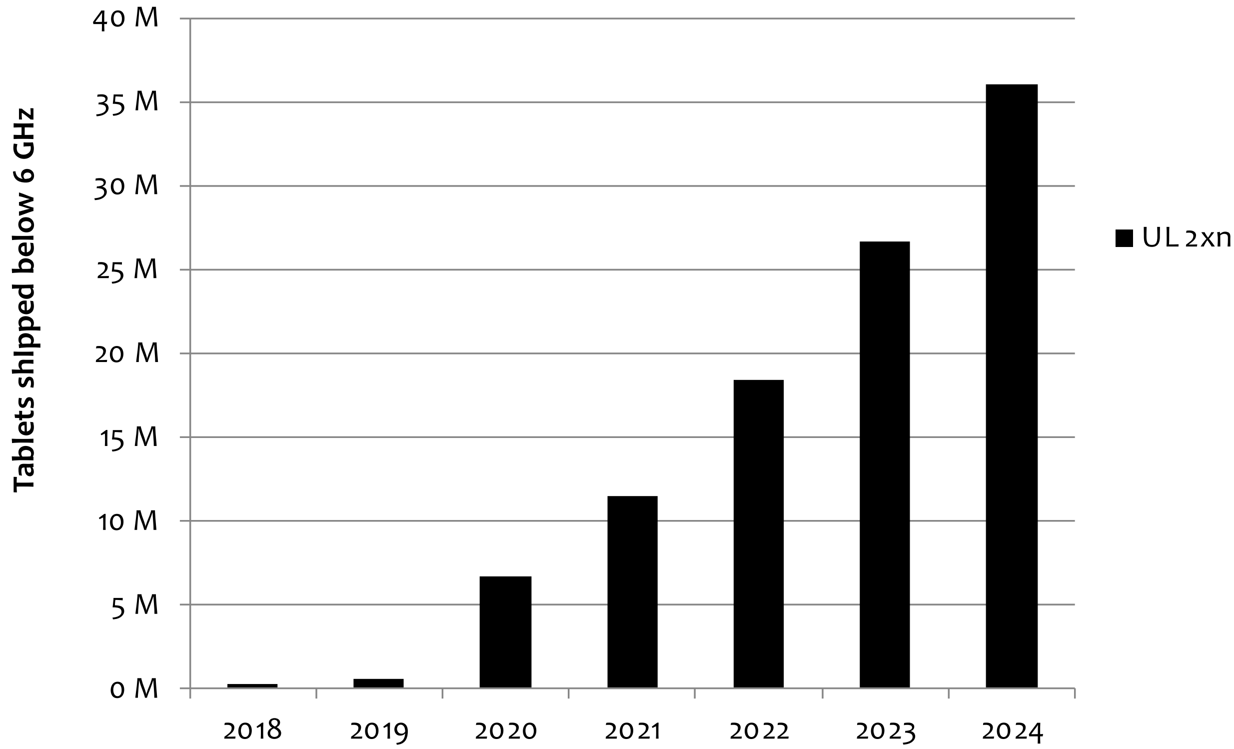


Chart 124: Tablets, Uplink MIMO Forecast, 2018-2024

Source: Mobile Experts

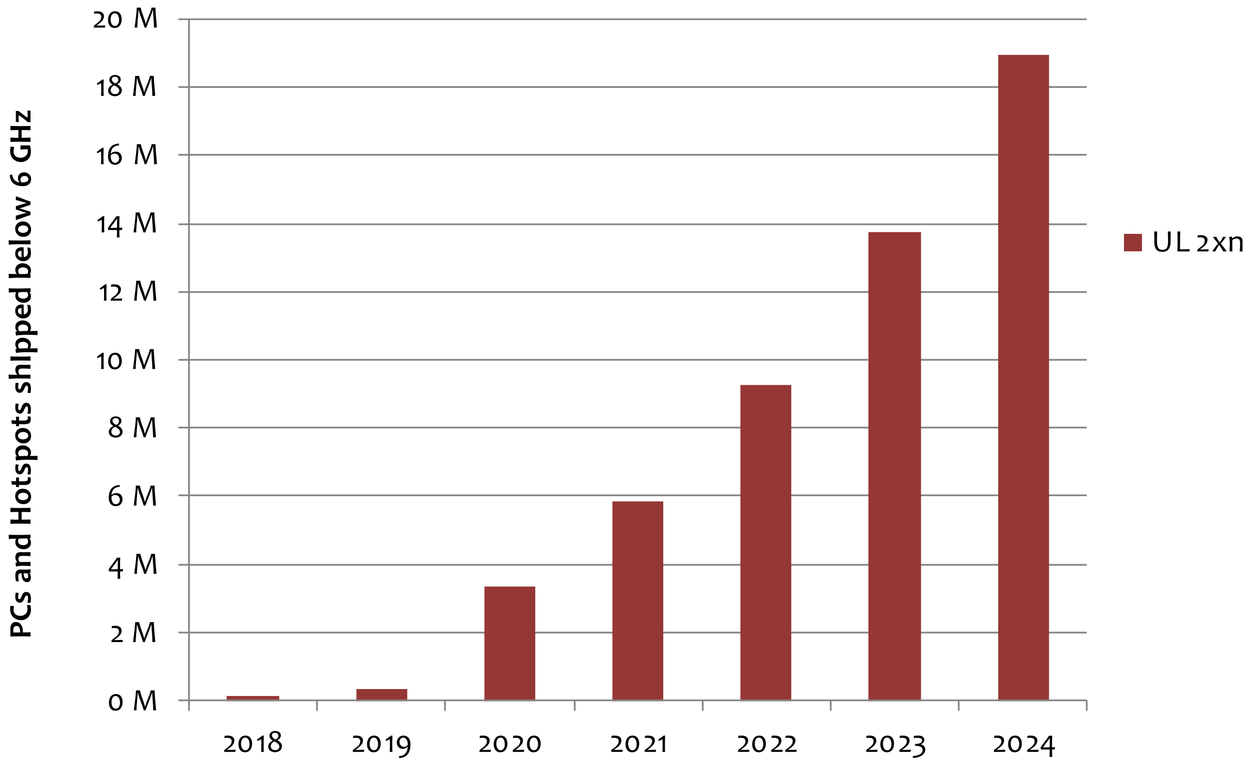


Chart 125: PCs and Hotspots below 6 GHz, Uplink MIMO Forecast, 2018-2024

Source: Mobile Experts

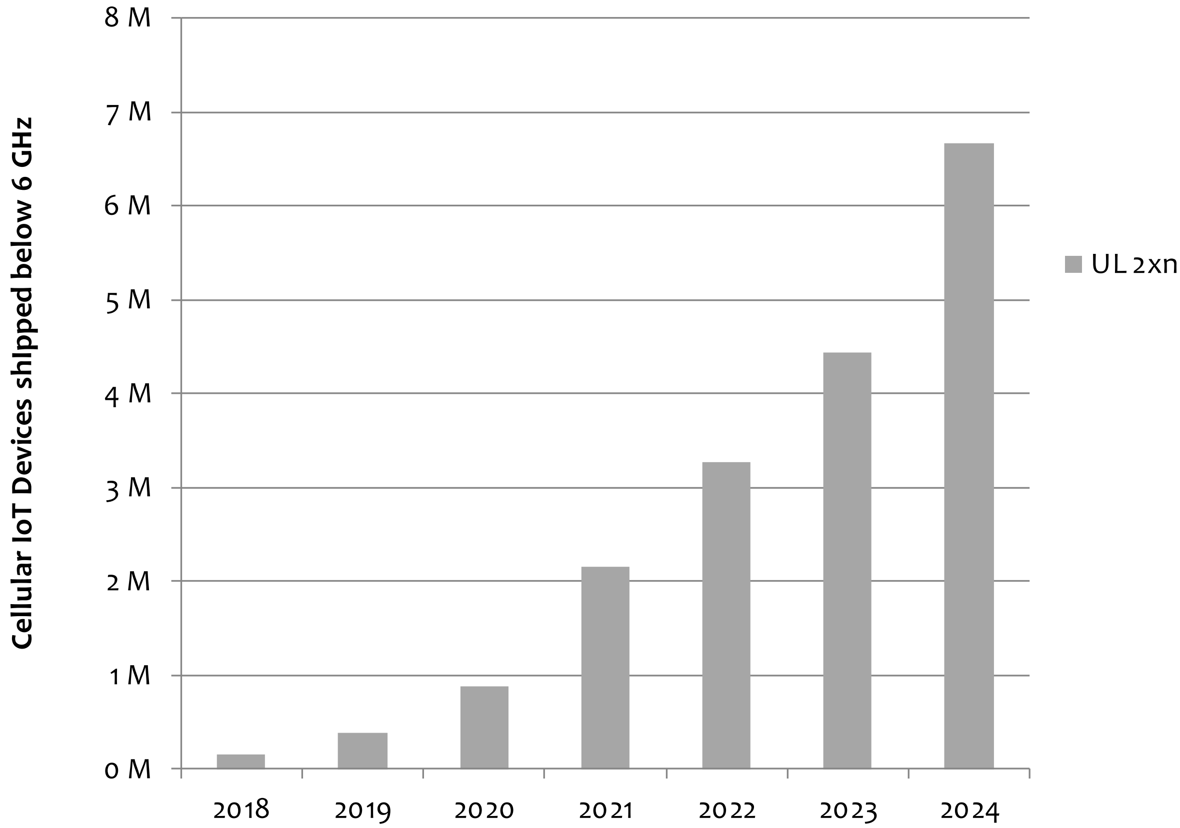


Chart 126: Cellular IoT Devices below 6 GHz, Uplink MIMO Forecast, 2018-2024

Source: Mobile Experts

13 COMPANY NOTES

AAC Technologies

AAC manufactures flex-film and LDS antennas, in addition to microphones and other non-RF components for handset applications. AAC acquired WiSpry Inc in May 2015, as a way to add MEMS tuning capacitors to their MEMS microphones. Because Cavendish Kinetics has found success with MEMS tuners, this company could come back onto the RF market.

Abtum

Abtum is a start-up company based in California, developing with innovative circuit technology that enhances filter and multiplexer isolation. The company's design IP is embedded in standard filter packages or RF front-end module substrates, resulting in improvements to the Tx/Rx isolation. They've successfully used the isolation improvement to implement a B1/B3 quadplexer using SAW technology, and some filters could be simplified to lower order. Their technology could also apply to BAW, ceramic, or tunable filters.

Airoha Technology Corp.

Taiwan-based Airoha supplies amplifiers, TxMs, LNAs, and switches to the low-tier Chinese handset market, with products in licensed RF as well as Wi-Fi and Bluetooth. Mediatek acquired Airoha during 2017, but so far we have seen no evidence of successful integration or envelope tracking co-design between Mediatek and Airoha. The relationship has resulted in higher market share for Airoha, compared with other local PA suppliers.

Akoustis Inc.

Akoustis uses a single crystal structure to fabricate bulk acoustic resonators, and has demonstrated high performance in the raw resonator. The company has strong materials fabrication and process control depth, and with newly acquired manufacturing assets should be able to produce high-performance filters with high yields. Akoustis has now successfully entered the production phase with their filters and may have an advantage in high Q, high bandwidth filters for 5G.

Apple

Apple is the #3 handset supplier on the market, with more than 200 million handset shipments per year. The company has floundered recently in trying to grow, and has been forced to return to Qualcomm for 5G modems after some bitter lawsuits. Apple is steadily losing its dominant position in the market.

Broadcom Ltd

The wireless group at Broadcom focuses on the high end of the market, with high-performance filters and highly integrated FEMs. Broadcom is strongest in the mid-hi band CFE market, where quadplexers and/or hexaplexers are used for key bands in the mid-hi range.

Cavendish Kinetics

Cavendish Kinetics is growing quickly, and they have now proven the high performance and high quality of their MEMs tuners and switches. Cavendish is in a great position as the only volume supplier of MEMS tuners, and has been able to establish a premium price over SOI switches. We expect strong growth to continue for a few years.

Eagantu

As a start-up company based in Israel, Eagantu has come up with an innovative way to implement filters using distributed elements in LTCC or PCB materials with high isolation. Their ACoN (Asymmetrical Coupled Network) architecture allows for high filter performance, and they're targeting some BAW/SAW applications. In particular the Eagantu technology could result in high performance in the 3-6 GHz bands, where wide bandwidth is key. The company also has some interesting ideas for high-isolation, small size circulators which could substitute for filters in some cases.

Global Foundries

Global Foundries is a leadings foundry for RF-SOI devices. Global Foundries also works with MEMS and Silicon-on-Sapphire processes, and we expect them to put multiple processes together for highly integrated RFICs for their partners. GlobalFoundries has the breadth of process capability to be a key player in 4G, 5G mm-wave, and IoT markets.

Huntersun (Hantianxia Electronics)

Huntersun is a PA supplier in China, and the company provides CMOS TxM modules for 2G and GaAs MMPA modules for 3G/4G. This year they introduced LNA products as well. They supply into Mediatek and Spreadtrum customers in entry-tier and some mid-tier Chinese handsets.

Intel

Intel Mobile Communications (previously Infineon) is a supplier of baseband modems and transceivers for the handset market. The company has floundered, reducing support in 2017 and 2018 to focus on Apple. During 2019 they lost their position at Apple as they fell behind on delivering a multimode 5G modem. At this point it seems that Intel is out of the handset market.

Lattice Semiconductor

Lattice is an FPGA and programmable logic supplier. The company supplies a MIPI controller/driver for handsets where the embedded controller in the baseband processor is inadequate (such as cases where more ports are needed than the chipset has available).

Lenovo (Motorola/Google)

Motorola was once a leading force in mobile handsets, but dropped incredibly quickly to second-tier status. The company designs and sells the DROID family of smartphones and has its strongest sales in North America. Google acquired the company and then sold it to Lenovo. Lenovo took over in October 2014 and has continued on. This company is notable for its quick release of the first 5G mm-wave handset using their MOD plug-in architecture.

Mediatek

Mediatek has grown to command substantial market share in the mid-tier with simpler smartphones, but is running a bit behind Qualcomm in terms of 5G modem capability. Mediatek bought a PA company (Airoha) two years ago, so we have been expecting some Envelope Tracking development but no products have come of that merger so far.

Murata Manufacturing Company

Murata makes SAW filters and ceramic devices for communications applications. The company has been very successful in competing with low-cost SAW devices and holds a solid market share simply based on huge SAW manufacturing capacity. Murata also acquired Renesas' power amplifier business, SAW device supplier RF Monolithics, and Peregrine Semiconductor over the years, and has put it all together in some CFE modules for local Japanese bands and some low-band CFE applications. They have recently introduced their "IHP" technology which is a thin-film SAW process for high performance.

NXP

NXP makes LNAs and switches using SiGe material, as discretes or with some LNA/switch integration. This is not the primary focus of the NXP RF product line but they have a minority share of the discrete market.

Peregrine Semiconductor/pSemi (Murata)

Peregine was acquired by Murata Manufacturing during 2014, and they've recently re-branded the company as pSemi. See Murata.

Qorvo

RFMD and TriQuint merged in early 2015 for form Qorvo, Inc. The combined company is a leading supplier of GaAs amplifiers, SOI switches, SAW and BAW filters, and related FEMs. Qorvo has successfully integrated PA and filter technology for high performance CFEs, and has high market share in key areas such as tuning devices. Qorvo has reached production at a flagship phone level with ET power supplies, in partnership with Intel… so Intel's exit from the modem market could be a concern. The company also acquired GreenPeaks in late 2016 to address the IoT market more fully. During the past year, Qorvo has been successful at penetrating the premium sockets in mid-high band CFEs with flagship customers.

Qualcomm (RF360)

Qualcomm is the leading supplier of baseband/transceiver chipsets for LTE mobile devices, and in the 5G market will have a significant lead over other players. Qualcomm formed a joint venture with TDK (RF360) to commercialize RF products, and retains the right to buy out TDK to take over the joint venture altogether, (the option becomes available in August 2019). We expect them to exercise the option and then operate as a subsidiary of

Qualcomm. Recent performance has shown that Qualcomm is effectively using the co-design of modem, software, and RFFE to achieve higher efficiency performance. We expect these co-designed products to be highly competitive, in multiple areas of the smartphone market.

R2 Semiconductor

R2 Semiconductor is a small company in Silicon Valley, focused on envelope tracking power supply development.   The company achieved production on the Samsung s5 Mini, introduced in mid-2014, combined with a TriQuint amplifier and a Samsung Shannon transceiver.   The ET world moved on, and as Samsung adopted Qualcomm and Intel ET PAs, R2 was left behind.

RDA Microelectronics

RDA is a fabless supplier of GaAs power amplifiers based in China.   Using a low cost strategy, the company began with 2G PAs and moved into into 3G with TD-SCDMA and WCDMA PA devices.   RDA integrates passive devices in clever ways to achieve low cost, and also supplies transceivers and baseband devices for feature phone and other low-end applications. The company is controlled by Tsinghua Unigroup (a state-controlled or state-owned company), along with Spreadtrum. Intel has also invested in Tsinghua.

Resonant Inc.

Resonant is a small California company with an innovative technique for filter synthesis which results in improved filter performance for standard technologies such as SAW or BAW.   Resonant has essentially created an ecosystem for fabless manufacturing of SAW filters with good performance, and their licensed designs have reached production volumes now. They have developed an advantage in design of wideband filters (600+ MHz bandwidth) with sharp skirts suitable for 5G using their patented XBAR resonator structure.

RF360 (Qualcomm/TDK)

RF360 is the joint venture set up by Qualcomm and TDK. See Qualcomm.

ROFS Microsystems

ROFS is the name of the Chinese company led by six individuals, which have been indicted by the US Justice Department for stealing trade secrets from Skyworks and Avago. These six people have allegedly "lifted" FBAR technology and other techniques from American suppliers. The company claims to have developed billion-unit capacity. ROFS did not respond to our request for an interview, but recently has introduced filters for Band 41 and for 3.5 GHz applications.

Samsung

Samsung is the leading mobile handset OEM worldwide, (and the leading smartphone vendor). They shipped about 300 million phones in 2018. The company leads through rapid innovation, and their pattern of testing new technologies on Korean domestic models works well to prove out new technologies before offering them to the world. Samsung develops its own baseband/processor chipsets, although it also uses Qualcomm chips.

Soitec

Soitec leads the market for substrates to support high resistivity silicon on insulator processing, supporting five major foundries with the substrates. Soitec pioneered a method of bonding thin single-crystal layers on high-resistivity substrates to achieve high performance in RF applications, and now supports multiple fabrication facilities with Silicon-on-Insulator wafers. They've also recently supported the industry's development of Piezo-on-Insulator (POI) technology, as well as acquired EpiGaN nv, to offer GaN wafers.

Spreadtrum/Unisoc

Spreadtrum has changed their working name to Unisoc. The company provides baseband modem ICs, and has a position in the lower tiers of the market (based on TD-SCDMA and TD-LTE entry level smartphones). Unisoc hasn't grown much as the mid tier of the market has moved up and their capability is still pretty basic. They've launched their first 5G modem but they are at least a year behind on the development of multimode 5G modem capability. The company was acquired by Tsinghua Unigroup in 2013 as part of a state-owned consolidation of mobile semiconductor suppliers. Intel also invested in Tsinghua during 2014. Tsinghua also invested in RDA, so there is some connection between Spreadtrum and RDA as well.

Sony Semiconductor

Sony provides digital tuning capacitors using thick-film metallization on GaAs substrates (known as an Metal Insulator Metal Capacitor). With this process, the company has been successful at capturing production orders from Samsung and is established as a supplier of switches and tuning elements in production volume. Sony develops specialty switches with dual-pole and even three-pole multi-throw switches.

Skyworks Solutions, Inc.

Skyworks has recently expanded their support of IoT applications as their opportunity in the smartphone market has slowed down. Skyworks uses its large GaAs fabrication capacity and separate foundry services to supply HBT amplifiers at low cost, and has established a low-cost SAW and TC-SAW filter capability. The company offers discrete switches and LNAs as well. The company still doesn't have filter technology that can compete at the FBAR/BAW level, but they do pretty well with TC-SAW technology for low-band and some mid/hi band applications.

Tai-SAW Technology Co. Ltd.

TST offers discrete SAW devices at low cost, and has continued to plug along with sales of discrete SAW filters. Based in Taiwan, TST has also developed BAW technology and VCXO related products.

Taiyo Yuden Company Ltd.

Taiyo Yuden makes SAW and FBAR devices, sometimes using combinations of SAW and FBAR technology in duplexers to avoid infringement of Broadcom patents. The company continues to support discrete filter applications but has not stepped up to CFE modules or other major growth segments in the RFFE market.

TDK-EPC (EPCOS, RF360)

Qualcomm folded EPCOS into the RF360 joint venture, but we view it as an acquisition since there is an "option to buy" in 2019, which we believe will be used. See Qualcomm.

TowerJazz

Tower Semiconductor acquired Jazz Semiconductor to form a combined foundry company with multiple semiconductor processes, and TowerJazz is currently considered a high performance "second source" to GlobalFoundries for most RF SOI products.

Vanchip

Vanchip is the name of the US corporation formed by multiple Chinese engineers that worked for RFMD and have been accused of stealing trade secrets. They provide a "Phase 2" Tx Module for Mediatek reference design customers, as well as switches and MMPAs for Spreadtrum and Qualcomm-based handsets. Vanchip has reached production volume in the range of 40-60 million PA units per year.

WIN Semiconductors Corp.

WIN Semiconductors provides GaAs and GaN foundry services from their base in Taiwan. The company has three fab facilities which together have an estimated capacity of 40,000 six-inch wafers per month. Overall, WIN has established itself as a key foundry to offload capacity for the major power amplifier suppliers. The company delivers a sizable portion of the world's GaAs capacity, and experienced double-digit growth in 2018. The mobile market represents about one-third of WIN's business.

WISOL

Based in Korea, WISOL is a steady supplier of merchant SAW filters. WiSOL has been able to step up to higher functionality, delivering some Diversity Modules and other integrated filter/switch devices, but the company has not grown its revenue since 2015.

X-FAB

X-FAB acquired the wafer operations of Altis Semiconductor. The operation supplies wafers for SOI and many other semiconductor applications, with a focus on RF applications. IBM chose Altis as a fab partner for RF-SOI before the acquisition by GlobalFoundries, so X-FAB provides a portion of the production billed by GlobalFoundries in the RF-SOI market.

14 GLOSSARY

2 x 2:	Two transmitters and two receivers
2 x n:	Two transmitters and any number of receivers
2G:	Second generation mobile service
3G:	Third generation mobile service
3GPP:	3G Partnership Project
4 x 2:	Four transmitters and two receivers
4 x 4:	Four transmitters and four receivers
4 x n:	Four transmitters and any number of receivers
4G:	Fourth generation mobile service (typically LTE and WiMAX)
5G:	Fifth generation mobile service (based on "new radio" NR standard)
8 x 8:	Eight transmitters and eight receivers
16T:	Sixteen transmitters/sixteen receivers
24T:	24 transmitters/24 receivers
ACLR:	Adjacent Channel Leakage Ratio
ASM:	Antenna Switch Module
ASP:	Average Selling Price
BAW:	Bulk Acoustic Wave
BPF:	Bandpass Filter
BST:	Barium Strontium Titanate (a ferroelectric material)
BT:	Bluetooth
BW:	Bandwidth
CA:	Carrier Aggregation
Cat-1:	Category 1 LTE M2M operation
Cat-0:	Category 0 LTE M2M operation
Cat-m1:	Category "minus 1" LTE M2M operation
Cat-m2:	Category "minus 2" LTE M2M operation (also known as NB-IoT)

CCFE:	Complete Front End
CDMA:	Code Division Multiple Access, a 2G standard.
CMCC:	China Mobile Communications Co
CMOS:	Complementary Metal on Silicon
dB:	Decibels (a relative measurement)
dBm:	Decibels compared to a reference (a power measurement)
DC/DC:	A direct current-to-direct current power supply
DL:	Downlink
DTC:	Digital Tuning Capacitor
EDGE:	Enhanced Datarates for Global Evolution (a 2.5G standard)
E-pHEMT:	Enhanced pHEMT GaAs process
EVDO:	Evolution—Data Only. This is a 3G standard related to CDMA.
ESD:	Electrostatic Discharge
ET:	Envelope Tracking
EVM:	Error Vector Magnitude (a measure of signal fidelity)
F/S:	Filter/Switch
FBAR:	Film Bulk Acoustic Resonator
FDD:	Frequency Division Duplexed
FEM:	Front End Module
FEMiD:	Front End Module in Duplexer (A Switched Duplexer Bank)
GaAs:	Gallium Arsenide
GHz:	Gigahertz
GPRS:	General Packet Radio Service
GPS:	Global Positioning System
Gs/s:	Gigasamples per second
GSM:	Global System for Mobile Communications
HBT:	Heterojunction Bipolar Transistor
HPUE:	High Power User Equipment

HSDPA:	High Speed Downlink Packet Access
HSPA:	High Speed Packet Access
HSPA+:	Evolved HSPA
HSUPA:	High Speed Uplink Packet Access
IC:	Integrated Circuit
IHP:	Incredibly High Performance (A Murata trade name)
IoT:	Internet of Things
ISN:	Infinite Synthesized Networks (a Resonant trade name)
IWPC:	International Wireless Packaging Consortium
kHz:	Kilohertz
LAA:	License-Assisted Access
LDS:	Laser Direct Structuring
LIPA:	Load Insensitive Power Amplifier
LNA:	Low Noise Amplifier
LoRa:	Long Range (An unlicensed IoT standard)
LPWA:	Low Power Wide Area formats for IoT
LTE:	Long Term Evolution (a next-generation air interface)
LTE Adv:	LTE Advanced, further evolution of LTE
LTE-FDD:	LTE using Frequency Domain Duplexing
LTE-M:	LTE variations for machine-to-machine communications
LTE-U:	LTE in the unlicensed bands
LWA:	LTE-WiFi Aggregation
M2M:	Machine-to-machine
MDM:	Multiple Duplexer Module
MEMS:	Micro-electro-mechanical systems
MHz:	Megahertz
MIMC:	Metal Insulator Metal Capacitor

MIMO:	Multiple Input, Multiple Output (refers to putting multiple signals into the air, and retrieving multiple signals from the air)
mm:	Millimeters
mm-wave:	Millimeter wave
MMPA:	Multiband Multimode Power Amplifier
mW:	Milliwatts
NB-IoT:	Narrow Band IoT
NFC:	Near Field Communications
NGMN:	Next Generation Mobile Networks organization
nH:	Nanohenrys (a measure of inductance)
ns:	Nanoseconds
OEM:	Original Equipment Manufacturer
OFDM:	Orthogonal Frequency Division Multiplexing
PA:	Power Amplifier
PAD:	Power Amplifier and Duplexer in a common package
PAMiD:	A common industry term that refers to Complete Front Ends
PAR:	Peak-to-Average Ratio
PC:	Personal Computer
PCB:	Printed Circuit Board
pF:	Picofarad (a measure of capacitance)
pHEMT:	Pseudomorphic High Electron Mobility Transistor
PMIC:	Power Management Integrated Circuit
POI:	Piezo on Insulator
ppm/degC:	Parts per million per Degree C of frequency drift in filters
pRF:	Radio Frequency
RF AI:	Artificial Intelligence applied to Radio Frequency devices
RFFE:	RF Front End
RFIC:	RF Integrated Circuit

ROI	Return On Investment
Rx:	Receiver
s:	Seconds
SAW:	Surface Acoustic Wave
SEC:	Securities and Exchange Commission
SiGe:	Silicon Germanium semiconductor material
SISO:	Single Input Single Output (Single transmit, single receiver)
SMMB:	Single Mode, Multi-band
SOI:	Silicon on Insulator
SOS:	Silicon on Sapphire
SRS:	Sounding Reference Signal
SVLTE:	Simultaneous Voice and LTE
TC-SAW:	Temperature Compensated Surface Acoustic Wave
TDD:	Time Division Duplex
TD-LTE:	Time Domain-Long Term Evolution
TD-SCDMA:	Time Division, Synchronous Code Division Multiple Access
TFAP:	Thin Film Acoustic Package
TF-SAW:	Thin-Film SAW
TIS:	Total Isotropic Sensitivity
TRP:	Total Radiated Power
TRX:	Transceiver
TSMC:	Taiwan Semiconductor Manufacturing Corp
Tx:	Transmitter
TxM:	Transmit Module
UE:	User Equipment
UL:	Uplink
UMTS:	Universal Mobile Telecom System
VSWR:	Voltage Standing Wave Ratio (a measure of impedance match)

W:	Watts (a measure of power)
WCDMA:	Wideband Code Domain Multiple Access
Wi-Fi:	Wireless Fidelity
WiMAX:	Worldwide Interoperability for Microwave Access

15 METHODOLOGY AND DEFINITIONS

Mobile Experts relies on interviews with industry suppliers for most of the data in our forecast. We conduct interviews with almost every supplier of RF components or modules, as well as handset, tablet, and IoT manufacturers.

We compare our interview inputs with information that comes from our research in mobile infrastructure. For key features such as MIMO adoption, CA adoption, 5G investments, and other areas, the infrastructure trends can dominate the overall timing. We check the timing and global scale of new feature adoption to align with handset timing.

Top-Down and Bottom-Up process

Mobile Experts uses a rigorous process to cross-check its forecast estimates. The overall process combines "top down" data and "bottom up" data to create the forecast in two separate ways. The assumptions, pricing estimates, and market shares are adjusted until the top-down numbers match with the bottom-up figures.

In the case of RF Front Ends, our top-down data sources consist of:

- Quarterly OEM reports of handset, tablet, PC, and other modem shipments
- Tear-down analysis of specific handset and tablet models
- Total shipments of the top 20 handset OEMs
- Separate research conducted by Mobile Experts on Cellular IoT device shipments, including interviews with more than 25 mobile operators and key industrial players
- Estimates by industry participants for the market size in each RF product area, as well as the number of devices used in each tier of the market.
- SEC filings and public comments from RF component suppliers, mostly regarding revenue figures.

The bottom-up forecast inputs come from a huge variety of sources:

- Direct interviews with specific RF component vendors. Mobile Experts has interviewed more than 45 different companies in the course of creating this report.
- Direct interviews with mobile device OEMs. Through personal contacts, Mobile Experts is able to ascertain the technical direction for key platforms, and the leading vendors in supply of specific components.

- Pricing analysis. Mobile Experts gathers many conflicting data points regarding pricing in the market and cross-checks with multiple sources wherever possible.
- Shipment reports. Mobile Experts has agreements with more than 20 RF component suppliers, under non-disclosure agreements, to share shipment data in key areas to highlight the usage by frequency band, by air interface standard, or for new technology introductions. We never reveal the identity of these companies or their specific inputs.

The crucial step in verifying accuracy involved a comparison of the bottom-up shipment/ASP/revenue estimates to the top-down revenue reports from six leading RF component suppliers. The pricing assumptions and market share assumptions were adjusted so that these two methods matched within 5%.

Note that in reporting the market size for a specific technology within front end modules, Mobile Experts made some arbitrary assumptions about the value of each function in the FEM. Our assumptions are based on the estimates of key players at RF FEM suppliers, based on the *manufacturing cost of each function* within a FEM. The FEM content assumptions are listed in the Excel spreadsheet on the page marked "Assumptions".

Scope of this report

This market study is intended to thoroughly cover the licensed-band radio components in mobile devices and the introduction of multiple new technologies into the mobile RF Front End. The report is not intended to provide deep technical analysis, but instead aims to provide enough technical information to explain the fundamental advantages or disadvantages of one technology vs. another. The end goal of this project is to provide a vision of the future roadmap for mobile RF front ends, providing RF component suppliers enough information to plan their investments in new products over the next few years.

The market study's scope is limited to licensed cellular and LTE for unlicensed bands, and does not include Wi-Fi, Bluetooth, GPS, FM Radio, NFC, or any other radio modes in the handset. RF components intended for LTE signal processing in unlicensed bands are included in this forecast.

Similarly, the scope of this report does not cover Envelope Tracking power supplies or modems, although we acknowledge that these components have increasing influence over RF Front End choices. The strategic impact of modem and RFFE co-design is covered in our *Expert INSIGHT* series of strategic reports.

Definitions

Always, with forecasting of complex technology markets, the definition of each market segment is important for clear understanding. Some of our key definitions for RF Front Ends are listed below.

Definitions	Description
Antenna Aperture Tuning	Use of an RF switch or variable capacitor to change the resonant frequency of the antenna.
Antenna-plexer	A passive filter structure that separates GPS, Wi-Fi, and/or Bluetooth from licensed 3GPP signals, located near the antenna.
ASM	Antenna Switch Module, incorporating a multi-throw antenna switch and multiple ports for different bands. Some ASMs include filters but others do not.
Complete Front End (CFE)	Also known as a PAMiD, LPAMiD, or LPAF. An integrated module which contains power amplifier, transmitter and receiver filters, as well as the necessary switches to incorporate all RF functions between the transceiver and the antenna for a specific set of frequency bands. The new PA/LNA/Switch/filter modules for 5G are included in this category.
Diplexer	A filter component which breaks the spectrum into a low band and high band on separate RF paths.
Diversity Module (DRx)	A module with a band selection switch and multiple bandpass filters, typically applied to the diversity or MIMO antenna path. Most also include LNAs
Duplexer	A component which separates transmit and receiver signals, resulting in a single antenna port but two separate filters for Tx and Rx chains.
Envelope Tracking Power Supply:	A voltage supply for an amplifier which ramps supply voltage up and down quickly, following the waveform of the radio signal.
Extractor:	A passive filter structure that separates GPS from licensed 3GPP signals. Some also separate 2.4 GHz signals for Bluetooth or Wi-Fi.
FEM	Front End Module, which may incorporate any combination of amplifiers, switches, tuners, or filters. MMPAs are not counted in the FEM category even if they include switches, for clarity. MMPAs with filters or duplexers integrated are considered Complete Front Ends and are placed in the FEM category.
Filter	A component with only a single input and output, used in the RF chain to select the desired band
Hexaplexer	A filter component which divides the spectrum into six bands, without switches, for simultaneous operation.
Impedance Match Tuning	Use of variable reactance components to modify the interface between two RF components (i.e. filter and antenna)
Inter-stage Tuning	Adjustment of capacitance or inductance values between stages of amplifiers or filters
Low Noise Amplifier (LNA)	An amplifier component used in the receiver chain. Most are integrated with diversity modules or other FEMs but some are used as discrete devices.
MMPA	(also known as MMMB) A multi-mode, multi-band PA component which handles more than one air interface standard and more than one band through a single RF path. MMPAs normally include switches at the output. A quad-band GSM/EDGE PA is not counted as an MMPA even though multiple bands and modes are handled....we require 3G/4G modes to qualify as an MMPA.
Multiplexer	A filter-based module which breaks the band up into multiple paths without using switches.
Passive Filter Bank	A filter-only module with multiple filtering components. This is counted in the Discrete Filter category despite a higher level of integration, because in the marketplace these products can be addressed by filter-only competitors.
Power Amplifier	A single package which may contain multiple die, used only for signal amplification to +20 dBm or more.
Quadplexer	A passive filter structure that separates the signals in four frequency bands, without switches, for simultaneous operation.
Switch	A component which only directs RF signals to different paths, without filtering or amplification. Switches used to change antenna length are counted as "tuners"
Switched Duplexer Bank	Also known as a FEMiD, a Switched Duplexer Bank includes band selection switches ad multiple duplexers.
Transfer Switch	A multi-pole, multi-throw switch that is used to "swap" antennas when the main antenna is impaired by the user's grip or other external objects. Most handsets use a DPDT switch today but 4P4T is likely for 4x4 MIMO cases.
Transmit Module	A PA integrated with antenna switching, which does not include ALL of the filters for the relevant bands. A Tx Module which integrates all of the filters would be considered a Complete Front End.

Figure 37: Definitions of product types

Source: Mobile Experts. See the first page of mexp-rffe-19.xls

Definitions	Description
Multimode:	Capable of simultaneous operation in multiple modes and at multiple bands
Reconfigurable	Capable of one air interface standard at a time, but adaptable to multiple standards
Single-mode:	Capable of only one air interface standard (Note: GSM/EDGE is considered a single mode)
RF Artificial Intelligence	The use of advanced learning algorithms in the modem to adjust large numbers of tuning elements in the RF Front End. This approach is used for digital self-calibration of each handset.
RF Path	Each different mode and frequency band is counted as an individual RFFE path. Because almost every different band requires a different RF filter, the RF signal follows a distinct path through the handset for each mode. Mobile Experts counts RFFE paths as a method to estimate total numbers of filters and other components.
RFFE-Standard	Each air interface standard handled by a terminal is counted as an individual RFFE-Std. Because many handsets handle multiple modes, this is a construct which is used to estimate component shipments. Note that Mobile Experts no longer uses this metric as a tool for estimating market size as of May 2018.
m x n MIMO	MIMO is designated by numbers of transmitters and receivers differently for uplink and downlink. Mobile Experts uses the first number, m, to designate the number of transmitters and n to designate the number of receivers.

Figure 38: Definitions of key terms

Source: Mobile Experts

Definitions	Description
Premium Tier Smartphone	A handheld device a high level operating system that sells for more than $500. This tier generally includes more than 18 frequency bands, and during 2018 included CA, TDD, FDD-LTE.
Mid Tier Smartphone	A handheld device a high level operating system that sells for between $200 and $500. This tier generally includes 5-18 frequency bands. During 2018, these units generally had a more fluid market for modems,with 5-mode operation and some CA or 4x4 MIMO.
Entry Level Smartphone	A handheld device a high level operating system that sells for below $200. This tier generally includes 3-10 frequency bands with limited features.
Feature Phone	A mobile phone without a High Level Operating System.
Tablet	A mobile terminal with the communications module embedded in a panel-style computer. Distinguished from PC applications by the user interface (touchscreen vs keyboard)
PC module	A communications module either embedded in a Personal Computer or provided as a USB dongle. Distinguished from tablets by user interface (keyboard vs touchscreen)
CPE	Customer Premises Equipment for fixed-broadband applications. Fixed CPEs are counted in the "hotspot" category in this forecast.
Hotspots	Either plugged in or working by battery, a modem which functions on mobile standards to provide local Wi-Fi access is known as a mobile hotspot.
IoT	A communications module for automated use by local embedded applications… not for direct human use. Internet of Things refers to new battery-optimized formats such as LTE Cat-M, NB-IoT, and EC-GSM.
M2M	A communications module for automated use by local embedded applications… not for direct human use. M2M refers to the legacy standards, GSM, 3GB53:C58, and LTE Cat-4 and above.

Figure 39: Definitions of terminal types

Source: Mobile Experts